DIGITAL ADVANCED DESIGN

TRANSITIONAL INDUSTRIAL APPROACHES FOR SUSTAINABLE INNOVATION

edited by
Flaviano Celaschi
Laura Succini
Michele Zannoni



Bologna
University Press


ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO
DI ARCHITETTURA

Collana del Dipartimento di Architettura – DA
Dottorato in Architettura e Culture del Progetto
Alma Mater Studiorum – Università di Bologna
Direttore del Dipartimento: Fabrizio Ivan Apollonio

Comitato Scientifico:
Cristina Gonzalez Longo, Carola Hein, Piotr Kuroczynski. Dijon Moraes jr., Ana C. Mourao Moura, Henrik Reeh, Rosa Schiano-Phan, Uwe Schroeder

Comitato di Indirizzo: Collegio del Dottorato in Architettura e Culture del Progetto

Tutti i contributi pubblicati all'interno della Collana sono sottoposti a un processo di *double-blind peer review*.



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA | DIPARTIMENTO DI ARCHITETTURA



This study was funded by the European Union - NextGenerationEU, in the framework of the "MICS - MADE IN ITALY CIRCOLARE E SOSTENIBILE" (PNRR - Missione 4 Componente 2 - Investimento 1.3 - Codice progetto PE00000004 - CUP J33C22002950001). The views and opinions expressed are solely those of the authors and do not necessarily reflect those of the European Union, nor can the European Union be held responsible for them.

Fondazione Bologna University Press
Via Saragozza 10, 40123 Bologna
tel. (+39) 051 232 882
ISSN 2385-0515
ISBN: 979-12-5477-602-5
ISBN online: 979-12-5477-603-2
DOI: 10.30682/9791254776032

Copyright © Authors 2025
CC BY 4.0 License

www.buponline.com
info@buponline.com

I diritti di traduzione, di memorizzazione elettronica, di riproduzione e di adattamento totale o parziale, con qualsiasi mezzo (compresi i microfilm e le copie fotostatiche) sono riservati per tutti i Paesi.
L'Editore si dichiara disponibile a regolare eventuali spettanze per l'utilizzo delle immagini contenute nel volume nei confronti degli aventi diritto.

In copertina: immagine realizzata dagli Autori
Progetto grafico: Gianluca Bollina-DoppioClickArt (Bologna)
Impaginazione: Oltrepagina (Verona)
Prima edizione: giugno 2025

Digital Advanced Design

Transitional Industrial Approaches for Sustainable Innovation

edited by Flaviano Celaschi, Laura Succini, Michele Zannoni

Bologna
University Press

Summary

9 *Introduction*
Flaviano Celaschi, Laura Succini, Michele Zannoni

11 *Digital Advanced Design as a framework to integrate knowledge and accelerate industrial innovation processes*
Flaviano Celaschi, Laura Succini, Michele Zannoni

DIGITAL DESIGN FOR MANUFACTURING

25 *Towards sustainable transformative factories with AI-based Human-Machine Interaction, Virtual Prototyping, and industrial orchestration*
Alberto Amico, Patrizia Cavalloro, Marcello Cinque, Davide De Vita, Stanislao Patalano, Andrea Rega, Virginia Vignali, Michele Zannoni

53 *Novel operator-centric digital technologies for a sustainable industrial workplace*
Francesca Calabrese, Marco Carricato, Edoardo Idà, Andrea Lucarini, Roberto Meattini, Maria Elena Nenni, Gianluca Palli, Alberto Regattieri, Filippo Zoffoli

65 *Life beyond Space: Responsible Advanced Design for new balances between space habitats and the human factor*
Laura Succini

89 *Advanced design strategies for space habitats: Bridging human factors and digital tools for enhanced living environments*
Veronica Pasini, Carolina Beccari, Valentina Gianfrate, Lucia Grizzaffi, Raffaele Montemurro, Lorenzo Rocci, Andreas Sicklinger, Elia Sindoni, Laura Succini

DIGITAL DESIGN FOR ADVANCED INTERACTION

123 *A reliable, affordable, low-cost, and open-source tool for fabric surface acquisition for the textile industry*
Riccardo Foschi, Federico Ponchio, Paolo Cignoni

141 *Haptic perception and enhancement of the interactive textile XR experience*
Michele Zannoni, Roberto Saponelli, Diego Pucci, Ludovica Rosato

155 *Next-Gen textile industry: From digital acquisition to displacement mapping*
Gaia Ghidoni, Riccardo Foschi, Martin Huska, Serena Morigi

177 *Artificial Intelligence and extended reality in fashion: Creativity and heritage preservation in the 2D-3D transition*
Pasquale Cascarano, Gustavo Marfia, Irene Calvi, Eleonora Stacchiotti

193 *Grounding future scenarios of technology-enhanced fashion heritage: A preparatory study for the storytelling of Made in Italy*
Irene Calvi, Eleonora Stacchiotti, Pasquale Cascarano, Gustavo Marfia

DIGITAL DESIGN FOR KNOWLEDGE SHARING

209 *Human and artificial elements in foresight: Cyber-creativity at the service of sustainable futures*
Ilaria Rinaldi, Irene Coletto, Angela Faiella, Stefano Rini, Giulia Maria Vavassori, Giovanni Emanuele Corazza

225 *From individual to organizational brain. Combining cognitive training, mindfulness and organizational innovation to enhance sustainable foresight capabilities of SMEs*
Giorgio Casoni, Flaviano Celaschi, Valentina De Matteo

245 *Sustainability transitions and back-casting for the Italian fashion industries*
Marco Bellandi

257 *FuturE-Pack. Toward a taxonomy of smart solutions for advanced packaging design*
Erik Ciravegna, Silvia Barbero, Davide Pletto, Mariapaola Puglielli, Martina Spinelli

277 *FuturE-Pack. Life Cycle Sustainability Assessment in advanced packaging design*
Erik Ciravegna, Caterina Antonia Dattilo, Massimo Delogu, Veronica Pasini

303 *Digital Waste Passport. Design a cross-sectorial platform of services to facilitate textile SMEs of Made in Italy in achieving traceability and circularity*
Debora Giorgi, Marco Bellandi, Claudia Morea, Chiara Rutigliano, Luca Incrocci, Matteo Bertelli, Elizaveta Stark

321 *Processes for managing and designing circularity in the Italian furniture industry. Current practices and future strategies for tools of interconnectivity*
Lorenzo Imbesi, Sabrina Lucibello, Emanuele Panizzi, Serena Baiani, Viktor Malakuczi, Paola Altamura, Luca D'Elia, Carmen Rotondi, Mariia Ershova, Gabriele Rossini

DIGITAL DESIGN FOR CIRCULAR MATERIALS

337 *LCA analysis of indoor covering solutions. Comparison of ceramic tiles, vinyl tiles, and laminated elements with sustainable materials*
Stefano Maretti, Alessandro Messori, Margherita Bandini, Michele Zannoni, Veronica Pasini

363 *Innovative materials for a more sustainable textile industry: Bio-based polymers and recycled fibers – A short review*
Fabrizio Cavani, Tommaso Tabanelli

375 *Use of recycled ceramic as cement substituent for a circular Made-in-Italy furniture industry*
Lucia Ferrari, Elisa Franzoni

387 *The next steps of the of the Spoke 1's project.*
Digital platform design for the sustainable transformation of the Made in Italy manufacturing industry
Marion Josserand, Michele Zannoni, Laura Succini

INTRODUCTION

Flaviano Celaschi, Laura Succini*, Michele Zannoni**

This research presents the launch of ten innovation fronts developed in parallel that will be followed in the ongoing projects by a phase of experimental testing and development of demonstrators, prototypes and living labs to validate methods and approaches for circular and sustainable design. The research is developed within *Spoke 1* of the extended partnership MICS (*Made in Italy Circolare e Sostenibile*), part of PNRR Mission 4 funded through the NextGenerationEU program with the aim of developing an innovation for the development of a new production system. With a focus on Digital Advanced Design, Spoke 1 explores how design and digital innovation can support the sustainable and circular transformation of three key *Made in Italy* sectors—furniture, fashion and automation—by strengthening the skills of industrial designers through knowledge, digital tools and interoperable processes.

The research, dedicated to *Digital Advanced Design: technologies, processes and tools*, involves several departments of the University of Bologna and other Italian universities, national institutions, leading companies in the relevant sectors, and additional research groups and entrepreneurial entities activated through Cascade Calls.

Through four thematic clusters—*Digital Design for Manufacturing, Digital Design for Advanced Interaction, Digital Design for Knowledge Sharing, and Digital Design for Circular Materials* — the goal is to develop a portfolio of accessible digital tools that enable industrial designers to orchestrate complex choices oriented to sustainability and circularity from both tangible and intangible points of view, in continuous innovation along the production chains of *Made in Italy*. In addition, from ongoing research is emerging the figure of the *Transitional Industrial Designer*, a designer capable of connecting knowledge systems and production systems, through anticipatory actions, continuous

**Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

and punctual data control systems and interdisciplinary contamination processes.

The publication closes with a preview of future developments related to Spoke's digital portfolio, a tool developed as an infrastructure to support the sustainable transformation of the Italian manufacturing system.

DIGITAL ADVANCED DESIGN AS A FRAMEWORK TO INTEGRATE KNOWLEDGE AND ACCELERATE INDUSTRIAL INNOVATION PROCESSES

Flaviano Celaschi, Laura Succini*, Michele Zannoni**

1. Digital Advanced Design within the *Made in Italy Circolare e Sostenibile* (MICS) Project

The PE11 *Made in Italy Circolare e Sostenibile*[1] (MICS)[2] Extended Partnership followed the goal set by the Next Generation Europe call to integrate several aspects that continue to limit industrial and social innovation today:

- Integration between different scientific sectors within the same university (to overcome the problem of knowledge closed in sectoral silos);
- Integration among experts of knowledge of the same scientific sector acting in different institutions and universities;
- Integration between academic research and applied research in companies or external laboratories, as well as sharing and collaboration among university researchers and industrial researchers-consultants working in companies;
- National collaboration on policies to support southern development in research and entrepreneurship;
- Gender rebalancing in research for innovation activities.

PE11 insists on the need for these different integration fronts to be supported as early as basic research (TRL 1-4) and expects the entire whole project to be developed in partnership between the actors described above in order to accelerate the process in a continuous *Open Innovation* perspective. This volume collects the scientific production carried out by a division (called Spoke 1) of this complex national research group. It consists by 32 researchers structured in 7 different departments of the Alma Mater Studiorum - University of Bologna, including the

**Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

researchers working in the 4 external institutions/universities (CNR; University of Florence; Sapienza, University of Rome; Federico II, University of Naples). The team of researchers involved represents a dozen different scientific sectors and adds up to the work developed by 32 researchers, research fellows and PhD students, recruited with the resources of the call, as well as all researchers involved in the following leading companies based in Italy: Thales Alenia Space Italia, AEFFE group, SACMI, SCM group, Italtel S.p.A. To this large group are added the contributions obtained by involving 6 aggregated teams of companies and research institutions involved through the Cascade Calls.[3] Thanks to this pool of actors, a total of 16 major basic research projects have been developed with the aim to increase the competitiveness of Made in Italy companies on the issues of sustainability and circularity.

The focus of our attention was the production processes and the products of three key Made in Italy sectors (Furniture, Fashion, Automation) that can achieve more efficient levels of sustainability and circularity and thus ensure that the Italian production system can face a market that tends to be more and more demanding (both domestic and export), and align with the requirements of reducing the ecological footprint on the Planet. The MICS Foundation has developed a three-year work plan that unfolds over eight Spokes (research lines covering different topics, such as materials, technologies, processes and organization, design, market and distribution). The University of Bologna, with the research group called Spoke 1, worked to the theme of *Digital Advanced Design*. Made in Italy products are the integrated result of sensitivity, cultures and centuries-old heritage, on the one hand, of a scientific approach, renowned performance, extreme customization, advanced technologies, controlled costs, precision and speed of response, on the other. So far, not as high attention and investment has been placed, generalizing the phenomenon, in the ecological impact and therefore in terms of equally high circularity and sustainability.

Spoke 1 focuses its efforts on fostering effective integration among the three key factors described above. In synergy with the other research it identifies Transitional Industrial Design as a strategic node in the innovation system envisioned

by the MICS Foundation. This refers to a professional, internal or external to the lead company in the process, who must be put in a position to enhance his or her sensitivity and skills in circularity and sustainability. This development occurs primarily by enabling digital access to knowledge, processes, tools, methodologies and stakeholder networks. Indeed, in the Fifth Technological Revolution, after the development and diffusion of data-enabling technologies, the effort to consider sustainability and circularity of the processes and goods produced is brought into focus. As the Spoke 1 research team, we can virtually represent an open linear chain describing the set of the combined steps in the process of the production chains. Knotting the ends of this chain generates a continuous circular path, in which each output (tangible or intangible) is bound to turn into inputs, either within the same process or into new and other productive and reproductive pathways. In this circular chain, we have hypothesized that the figure of an industrial designer capable and equipped to collect information in real time from each step of the supply chain is essential and becomes skilled in orchestrating this *concert of actors and steps* without losing control of knowledge and the possibility to correct production action in the various areas.

Industrial designers operating in the key sectors of Made in Italy come from diverse educational backgrounds (engineering, design, architecture, chemistry, IT, etc.) and therefore tend to adopt a predominantly vertical approach to the multiple critical factors that influence the creation of sustainable and circular value. Leveraging the potential of digital technologies, this research aims to expand the interoperable availability of knowledge, technologies, and processes, which in an integrated way, inform design decisions, strengthening the industrial designer's competencies in less consolidated fields of knowledge. We research on a cluster of tools that makes the interaction between vertical experts and decision-making synthesis subjects (entrepreneur, designer, manager, creative, customer) more agile and feasible. Our goal over the 36 months is to develop a portfolio of processes, tools, and targeted knowledge, digitally accessible to industrial designers of Made in Italy sectors, regardless of their training profile/educational background. This portfolio is intended to provide information that continuously and effec-

tively support synthesis decisions, particularly with regard to the sustainability and circularity challenges that are feasible at an industrial level.

In the basic research phase, the Spoke identified the following vertical and parallel work packages (WPs):

- Area of expertise on materials and chemical and biological processes;
- Area of expertise on mechanical and electronic technologies related to automation processes;
- Area of expertise on image processing and digital representation of reality;
- Area of expertise on logistics, packaging, wrapping and communication processes of products.

In addition to the following systemic integration WPs:

- Analysis of the solutions available within a portfolio of specialized digital practices;
- Analysis of the state of the processes, systems and tools in use in informed support for design synthesis decisions and evaluation of impact performance;
- Study of change and anticipation of medium-term scenarios to configure times and results.

Following the vertical research on individual projects, the activity was shifted towards creating interconnections between different parallel initiatives. The goal is to develop experiments applicable to the three key sectors identified in the call for proposals, allowing for the evaluation and refinement of the emerging results. The phases of exploitation and communication of the outcomes do not only occur at the end of the research, but were integrated throughout the entire process. This approach aims to disseminate not only the final results, but also the intermediate outputs—such as semi-finished products and research components—that can be exploited beyond the pre-established objectives, thus enhancing each intermediate phase as well as the underlying methodologies for their development.

2. Spoke 1. Methodology research

The challenges of circularity and sustainability are deeply embedded in the concept of "wicked problems" (Rittel & Webber, 1973), understood as issues distributed across time and space that exert a profound influence on human life (Morton, 2013).

Addressing such complex challenges demands a holistic vision, interdisciplinary collaboration, and a continuous search for innovative solutions. Within the broader context of business and industrial production, Spoke 1 approaches sustainability through two interrelated dimensions of responsibility: the tangible—including environmental and social factors—and the intangible, rooted in ethical, inclusive, and transparent practices.

To meet these demands, Spoke 1 adopts the *Responsible Advanced Design* (RAD) approach (Succini & Ciravegna, 2022; Succini, 2023), which integrates intangible values—"ethics, inclusion, care, gender equality, transparency, responsible thinking, time, and open access—with tangible principles such as recyclability, reuse, and the selection of sustainable materials." (Succini et al., 2024, p. 100). RAD seeks to define new design paradigms capable of generating high social and environmental impact, while fostering competitive advantage by embracing the diversity of stakeholders, optimizing available resources, and enhancing the identity of local territories.

Thus, designing, implementing, and disseminating advanced digital design solutions extends beyond mere technological adoption: Spoke 1 envisions digital tools and systems as key drivers of circular and sustainable innovation across Made in Italy industries, empowering industrial designers to develop new product-service systems and strengthen their capabilities to navigate transitional phases.

The RAD approach addresses several key transitions, in particular:

- *Shift from the "supply chain" to the "value chain"*
  The traditional supply chain focuses on the procurement of materials and the delivery of goods to the customer. In contrast, the new research process moves towards the concept of the "value network" (Giardina, 2023), disrupting the linear relationship between customer and supplier and

embracing an approach where collaboration, resilience, and transparency become crucial aspects of the transition.

- *Shift from efficiency to the concept of human and environmental prosperity*
  This transition is based on redefining consumption models, improving minimum living standards, and raising consumer awareness of their role along the value chain. Human well-being within our current societies represents a challenge that demands new forms of design, production, and consumption, where sustainability, inclusion, and collaboration are key aspects of transformation processes.
- *Strengthening of open innovation*
  Creativity, anticipation, and adaptability are the key words underpinning this development. Starting from the concept of collaborative innovation, it is necessary to conceive and implement new ways of working and doing business. The impact of cross-disciplinary and cross-sectoral contamination—involving academia, institutions, industry, and society—can benefit both the competitiveness of industrial sectors and the achievement of greater sustainability and circularity in products and services.

3. Spoke 1. Research clusters

In the overall development of the Spoke 1 project, the ten sub-projects initiated have given rise to four specific groups for the application of basic research:

- Digital Design for Manufacturing;
- Digital Design for Advanced Interaction;
- Digital Design for Knowledge Sharing;
- Digital Design for Circular Materials.

The main activities focus on human-machine interaction in transformative manufacturing, digital twins for textile design, circular materials for furniture, and system design tools for knowledge sharing.

The projects discussed encompass the design of physical, systemic, and symbolic elements and their impact on human

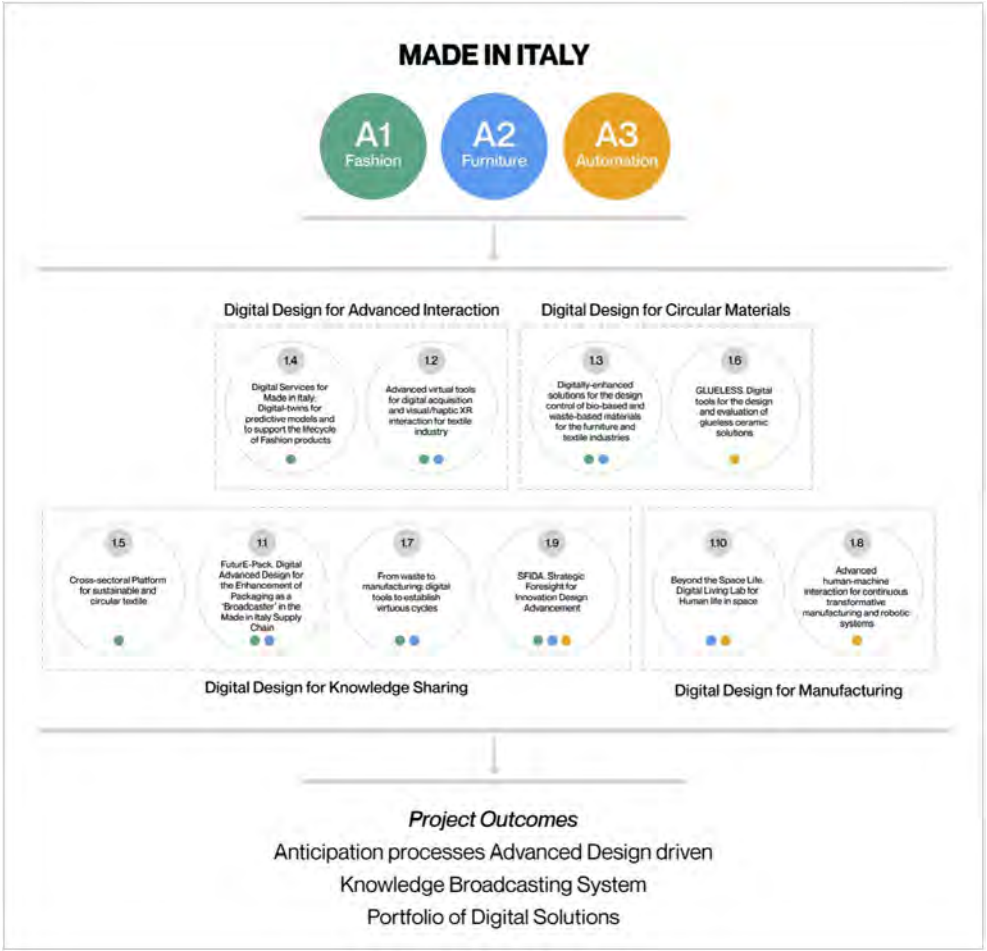
value and values. These include material objects, informational and communicative artefacts, services and experiences, new business models, and new ways of working based on cross-fertilization, all of which contribute to shaping the competitive identity of Made in Italy from the perspective of sustainability and circularity.

Based on these premises, the environment and digital transformation can be considered relevant for all companies pursuing growth, quality, and sustainability (Shinde et al., 2014). Since the purpose of Spoke 1 is the study of technologies, processes, and tools for digital advanced design, all ongoing projects regard digital transformation as a profound and accelerated evolution of activities, processes, skills, and business models aimed at fully exploiting the changes and opportunities offered by digital technologies and their impact (Betchoo, 2016) on businesses, organizations, and society.

To achieve these objectives, the research stream *Digital Design for Manufacturing* is oriented towards the design of digital models to enhance human-machine interaction, as well as robotic systems for transformative and continuous production; it also aims to improve human quality of life in extreme contexts, such as space habitats in microgravity conditions.

The thematic cluster *Digital Design for Advanced Interaction* focuses on the development of virtual tools for designers, particularly in the fashion sector, with the aim of enhancing haptic and visual simulations of fabrics within extended reality environments. In addition, it concentrates on the definition of digital twins to be used for simulation and predictive models, as well as to support the lifecycle of the fashion product design process.

The projects developed within the *Digital Design for Knowledge Sharing* research line are addressing the development of digital tools to facilitate knowledge gathering and information exchange, aiming to establish innovative methods of design, communication, and interconnection among different actors to promote virtuous cycles within the industry. Finally, the research strand *Digital Design for Circular Materials* research line is working on digital solutions for the design control and evaluation of biobased and waste-derived materials for the furniture and textile industries, as well as on more sustainable ceramic solutions (fig. 1).



1. Relationship among Thematic Clusters, Ongoing Projects and Spoke 1 Expected Outcomes.
All images are reproduced in color in the online edition of the book.

The four clusters share the following common objectives:

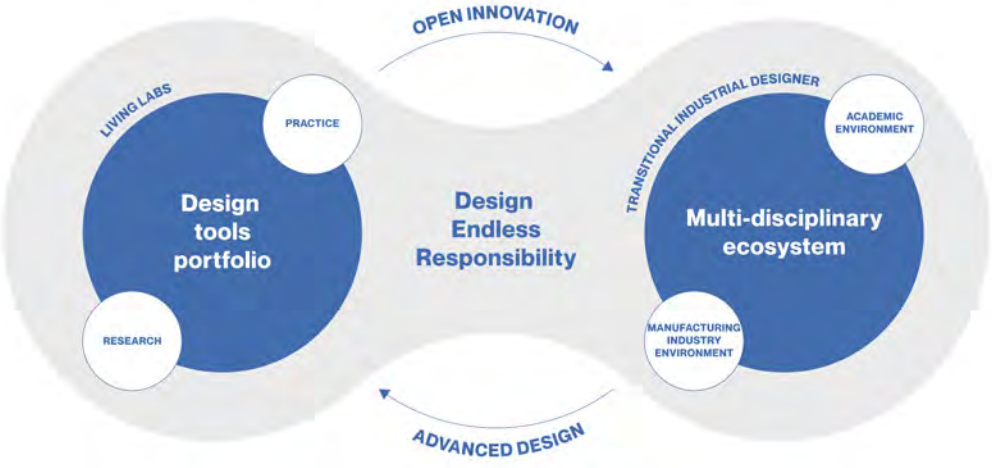
- To produce experiments and results aimed at developing a unified portfolio of digitally enhanced solutions to support, integrate, and validate decision-making, design, and production processes within the Made in Italy value chains;
- To activate and embed within the mindset of companies and designers anticipation processes driven by advanced design.

4. Towards the role of the Transitional Industrial Designer

Within these research clusters, the RAD approach provides a coherent framework for understanding innovation while emphasizing the transformative potential of adopting an integrated, anticipatory, and responsible mindset across the industrial ecosystem. This is achieved through the concept of *Design Endless Responsibility* (DER), where "the designer is called not only to connect and mediate the domains and stakeholders involved in the design process [...], but also to take into account the entire value chain, from ideation to end-of-life, considering the future impacts associated with each design phase." (Zannoni et al., 2024, p. 62).

DER serves as a system for assessing how, and to what extent, social, environmental, and relational impacts are addressed during the design process (fig. 2). This perspective is key in shaping the emerging figure of the *Transitional Industrial Designer* envisioned within Spoke 1.

The *Transitional Industrial Designer* thus acts as a mediator between production systems and knowledge systems, "taking into account the cultural, economic, and productive variables of the various ecosystems in which they operate, collaborating with industrial and academic stakeholders to redesign relationships, processes, and the use of resources." (Zannoni et al., 2024, p. 62). Moreover, the *Transitional Industrial Designer* leverages anticipation capabilities and impact analysis to develop design solutions aimed at promoting ecological and responsible transition. This designer must be able to work closely with industrial sectors and territorial communities, fostering more resilient and adaptable models in a continuously evolving environment (fig. 3).



2. The role of Design Endless Responsibility in the design process.



3. Characteristics of the Transitional Industrial Designer and its role in the territorial system.

In order to support the achievement of these objectives, seven Cascade Calls (BAC – in Italian Bandi a Cascata) have been launched since September 2024, involving companies and research centers predominantly located in Southern Italy.

These initiatives are designed to reinforce and expand the ongoing activities within the four research clusters, while simultaneously fostering innovation processes characterized by higher Technology Readiness Levels (TRLs).

This strategic approach not only facilitates the development of foundational models for sustainable innovation, but also enables the advancement of selected ideas toward experimental validation in real market conditions.

Conclusions

This book focuses on the first phase of Spoke 1's research activities (January 2023–November 2024) and provides a snapshot of the relationships, scientific investigations, and industrial research carried out within the ten projects that define it, presenting them according to the four research clusters previously introduced.

The publication closes with an essay dedicated to presenting the design process of the digital portfolio, its purpose, objectives and architecture. How this digital platform succeeds in collecting project outcomes and can become a system for the sustainable transformation of the Made in Italy manufacturing industry is described.

The seven BAC projects, however, are not described in this book, as they were launched during the final stages of the volume's drafting.

Notes

[1] MICS is an Extended Partnership financed by the MUR (Ministry of University and Research) thanks to the funds made available by the European Union as part of the NextGenerationEU program and represents one of the projects relating to Mission 4 of the PNRR "Education and Research."

[2] https://www.mics.tech/en/home/.

[3] https://www.mics.tech/progetti-bac/.

References

Betchoo, 2016
Betchoo, N. K. (2016). Digital transformation and its impact on human resource management: A case analysis of two unrelated businesses in the Mauritian public service. In *2016 IEEE International Conference on Emerging Technologies and Innovative Business Practices for the Transformation of Societies (EmergiTech)* (pp. 147–152). https://doi.org/10.1109/EmergiTech.2016.7737328

Celaschi et al., 2019
Celaschi, F., Formia, E., Iñiguez Flores, R., & León Morán, R. (2019). Design processes and anticipation. In R. Poli (Ed.), *Handbook of Anticipation* (pp. 773–793). Springer International Publishing. https://doi.org/10.1007/978-3-319-91554-8_48

Giardina, 2023
Giardina, C. (2023). Holistic approach in design research: Made in Italy circular packaging innovation by transitional industrial designers. *Diid — Disegno Industriale Industrial Design*, *79*, 21–33. https://doi.org/10.30682/diid7923b

Irwin, 2015
Irwin, T. (2015). Transition design: A proposal for a new area of design practice, study, and research. *Design and Culture*, *7*(2), 229–246. https://doi.org/10.1080/17547075.2015.1051829

Morton, 2013
Morton, T. (2013). *Hyperobjects: Philosophy and ecology after the end of the world*. University of Minnesota Press.

Rittel & Webber, 1973
Rittel, H. W., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, *4*(2), 155–169.

Succini, 2023
Succini, L. (2023). Leggere l'Innovazione Responsabile attraverso l'Advanced Design. In E. Formia, V. Gianfrate, & L. Succini (Eds.), *Design per l'Innovazione Responsabile. Guida per processi formativi in trasformazione* (pp. 21–36). Franco Angeli.

Succini & Ciravegna, 2022
Succini, L., & Ciravegna, E. (2022). Design and Responsible Innovation. Ethics and caring as keys to addressing contemporary crises. *Diid — Disegno Industriale Industrial Design*, *77*, 24–36. https://doi.org/10.30682/diid7722b

Succini et al., 2023
Succini, L., Celaschi, F., Ciravegna, E., & Pasini, V. (2024). Responsible Advanced Design. Achieving sustainability through collaborative processes. *Theme de Disseny*, *40*, 92–111. https://doi.org/10.46467/TdD40.2024.92-111

Zannoni et al., 2024
Zannoni, M., Succini, L., Rosato, L., & Pasini, V. (2024). Transitional Industrial Designer. La responsabilità di progettisti e imprese per una transizione sostenibile (Transitional Industrial Designer. The Responsibility of Designers and Companies for a Sustainable Transition). *AGATHÓN*, *15*, 332–343. https://doi.org/10.19229/2464-9309/15282024

DIGITAL DESIGN
FOR MANUFACTURING

DIGITAL DESIGN FOR MANUFACTURING

Within the *Digital Design for Manufacturing* research cluster, the progress of projects 1.8 *Advanced Human-Machine Interaction for Continuous Transformative Manufacturing and Robotic Systems* and 1.10 *Beyond the Space Life. Digital Living Lab for Human Life in Space*.

The contribution, "Towards Sustainable Transformative Factories with AI-based Human-Machine Interaction, Virtual Prototyping, and Industrial Orchestration," delves into human-machine collaboration, Virtual Prototyping, and software/network co-orchestration in advanced automation systems for the development of sustainable scenarios that can be enabled by a load-aware orchestrator. The second paper, "Novel Operator-Centric Digital Technologies for a Sustainable Industrial Workplace," explores predictive maintenance and reconfigurable robotic systems, with a focus on HMI technologies. It also outlines expected outcomes, including advanced tools for real-time mental load management and intuitive interfaces for interaction and programming of collaborative robots.

For project 1.10, the essay "Life Beyond Space: Responsible Advanced Design for New Balances Between Space Habitats and the Human Factor" presents methodology and actions taken to activate, in an experimental way, a process of shared knowledge among different actors and an interdisciplinary design path, open to contamination within and outside the Space domain. Finally, the essay "Advanced Design Strategies for Space Habitats: Bridging Human Factors and Digital Tools for Enhanced Living Environments" delves into one of the outcomes of the 1.10 project, illustrating the methodological process of advanced design applied to the configuration of space habitats oriented toward the psycho-physical well-being of future users and the flexibility and adaptability of environments.

TOWARDS SUSTAINABLE TRANSFORMATIVE FACTORIES WITH AI-BASED HUMAN-MACHINE INTERACTION, VIRTUAL PROTOTYPING, AND INDUSTRIAL ORCHESTRATION

Alberto Amico, Patrizia Cavalloro**, Marcello Cinque***, Davide De Vita***, Stanislao Patalano****, Andrea Rega****, Virginia Vignali*****, Michele Zannoni******

1. Introduction

Digital transformation in manufacturing requires rethinking fundamental processes, to seamlessly involve the human in the loop of the design, management, and continuous re-configuration of transformative factories. The adoption of digital approaches for machine management and digital prototyping can boost such involvement, towards an improved sustainability in automation not achievable with current solutions.

The research aims to address these problems from several intertwined perspectives that are needed to simplify and guide the work of operators, involving human-machine collaboration, Virtual Prototyping (VP), and software/network co-orchestration in advanced automation systems.

One objective of the research is to define a reference scenario, depicted in figure 1, where to challenge the advanced portfolio of solutions for advanced AI-based Human-Machine Interaction and orchestration of future transformative factories. The vision is to achieve sustainability by designing factories to be reprogrammable and, therefore, reusable components that can be activated only when needed by an intelligent orchestrator that knows the needs and load of its cluster. Human-Machine Interaction can become two ways, rather than passive only, harnessing the potentiality of AI. Finally, analysis and tests can be run on virtual prototypes, rather than or alongside their physical counterpart allowing for much more repeatable, sustainable, and cost-efficient analysis. The solution can be adopted by industrial designers, system administrators, and machine operators along all the layers of a typical cloud-edge-things infrastructure.

Authors are alphabetically listed

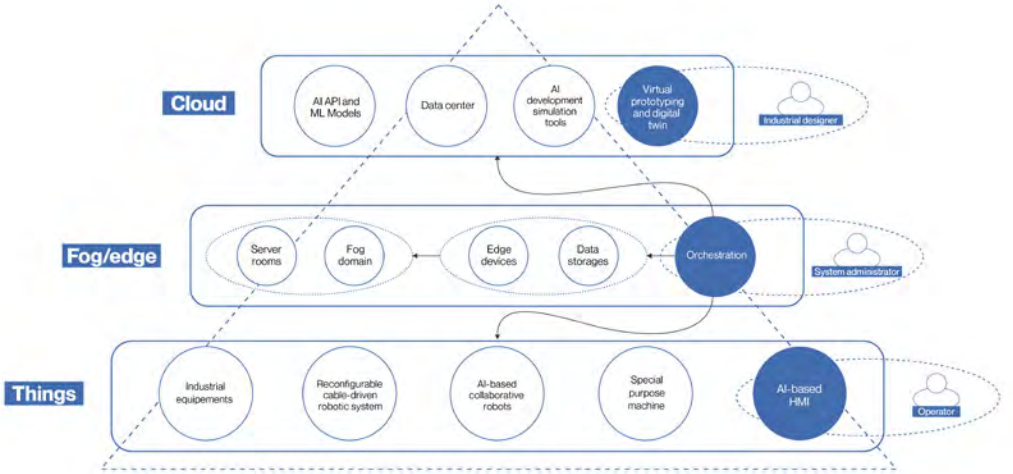
**ITALTEL, Palermo, Italy*

***ITALTEL, Milano, Italy*

****Department of Electrical Engineering and Information Technology, University of Naples Federico II, Italy*

*****Department of Industrial Engineering, University of Naples Federico II, Italy*

******Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*



1. Reference scenario and research architecture. All images are reproduced in color in the online edition of the book.

The first field of research related to AI-based HMI proof of concept concerns the definition of Human-Machine Communication based on a pro-active relationship allowing for transparent interaction; it addresses the improvement of working conditions and production flow, and the field of pro-active interaction and feedback through an artificial intelligence system in order to identify the ideal working conditions and optimize the production process. These aspects make it possible to create a system that enhances the creation of a collaborative environment between man and machine, overcoming the concept of only passive interaction, identifying the potential of human and artificial capabilities, and promoting diversity, and empowerment (Ionescu, 2022) and testing more sustainable industrial products.

Regarding Virtual Prototyping, namely a computer-based representation or simulation of a physical product, the significant increase in computing power over the last decade, and the development of high-fidelity simulation tools have meant that it can leverage cutting-edge tools to simulate and study the behavior of physical system with remarkable accuracy. Hence, virtual prototypes are becoming increasingly realistic with high-quality 3D representation thanks to the advancement of software, allowing for detailed and accurate simulations. Virtual Prototyping comprises many tools and approaches, ranging from Computer-Aided Design (CAD) modeling, including parametric modeling, freeform surface modeling, point clouds, and generative design, to systems modeling, e.g., agent-based modeling, or complex simulation and analysis, including Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD) (Kent et al., 2021). These examples of simulation techniques have reached unprecedented levels of sophistication helping engineers to identify and address potential issues early in the design process but also to reduce the need for costly physical prototypes and extensive testing, ultimately accelerating time-to-market.

Above all, the factory cell would fit in a cloud-edge, IOT paradigm, where heterogenous nodes (either specialized, general purpose or real-time) are managed by a high-level orchestrator that can activate idle servers on need and evaluate if an active one can handle extra load to reduce consumption, optimize the

resource management and not waste any processing capacity without losing on performance. The orchestrator will have the power to request, activate, or let go of extra computing power from server rooms or devices in the Fog/Edge layer, deciding on the most fitting solution according to load type, requirements, and latency, while heavy computation like ML-training, simulations, and digital twins can be hosted on the higher level harnessing the potentiality of cloud computing.

2. AI based HMI

2.1. State of the art

2.1.1. The early levels model and the debate on human-machine automation

The early groundwork in the domain of task distribution between the human and the machine was laid out right after the Second World War by psychologist Paul Fitts (1951) in a report on air traffic system studies. He provided a comprehensive list of tasks (tab. 1) applicable to both humans and machines, highlighting areas where one outperforms the other. Later Thomas Sheridan and Bill Verplanck (1978) defined 10 stages of the human-machine relationship from an automation perspective (tab. 2).

Tab. 1. The original Fitts list (1951).

	Humans appear to surpass present-day machines in respect to the following:		**Present-day machines appear to surpass humans in respect to the following:**
1	Ability to detect a small amount of visual or acoustic energy	7	Ability to respond quickly to control signals and to apply great force smoothly and precisely
2	Ability to perceive patterns of light or sound	8	Ability to perform repetitive, routine tasks
3	Ability to improvise and use flexible procedures	9	Ability to store information briefly and then erase it completely
4	Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time	10	Ability to reason deductively, including computational ability
5	Ability to reason inductively	11	Ability to handle highly complex operations, i.e. to do many different things at once
6	Ability to exercise judgment		

Tab. 2. The original levels by Thomas Sheridan and Bill Verplanck (1978).

Level	Description
1	The human who considers alternatives and makes and implements decisions
2	The computer offers a set of alternatives that the human may have ignored in the decision-making
3	The computer offers a restricted set of alternatives, and the human decides which to implement
4	The computer offers a restricted set of alternatives and suggests one, but the human still makes and implements the final decision
5	The computer offers a restricted set of alternatives and suggests one, that it will implement if the human approves
6	The computer makes the decision but gives the human veto option before implementation
7	The computer makes and implements the decision, but must inform the human after the fact
8	The computer makes and implements the decision, and informs the human only if asked to
9	The computer makes and implements decisions, and informs the human only if it feels this is warranted
10	The computer makes and implements the decision if it feels it should, and informs the human only if it feels this is warranted

Over time, they have been modified into four phases of automation: information acquisition, information analysis, decision or action choice, and action execution (Parasuraman, Sheridan & Wickens, 2000). These phases refine the discussions at each of the levels, but the underlying message is that the goal is full automation/autonomy. The ten levels of automation were changed, and the researchers propose a revisited version (tab. 3).

Tab. 3. The revised levels by Parasuraman, Sheridan & Wickens (2000).

Level	Description
high 10	The computer decides everything and acts autonomously, ignoring the human
9	The computer informs the human only if it, the computer, decides to
8	The computer informs the human only if asked, or

7	The computer executes automatically, then necessarily informs the human, and
6	The computer allows the human a restricted time to veto before automatic execution, or
5	The computer executes that suggestion if the human approves, or
4	The computer suggests one alternative, or
3	The computer narrows the selection down to a few, or
2	The computer offers a complete set of decision/action alternatives, or
low 1	The computer offers no assistance; the human must take all decisions and actions

2.1.2. The change of paradigm from interaction to cooperation

In the current production and design environment, the relationship between people, computer systems, and machines has experienced transformations from both a technological and a human perspective. The new modes of relationship allow to initiate experiments by moving from the concept of Human-Machine Interaction to Human-Machine Cooperation (Hoc, 2000) and heteromation (Ekbia & Nardi, 2014), introducing a collaborative and knowledge-sharing dimension between human and artificial agents through a distribution of activities and skills.

New technologies, such as smart systems based on artificial intelligence, within the manufacturing industry's production processes, enabled the creation of new development paradigms (European Commission, 2018) based on a proactive mode of relationship and feedback, making people and machines designing agents (Giaccardi & Nicenboim, 2020) they actively collaborate in the exchange of information towards process optimization, the introduction of new ways of controlling machines and collecting data from the environment and the user's intention (Nothdurft, Ultes & Minker, 2015). The information flow between users and systems is a fundamental element for the successful performance of production processes. The proposed integration of an intelligent system within these frameworks can have an impact on how information is delivered back and how it relates to the machine by examining the correct synergistic mode of relationship between human and artificial agents.

According to these insights, a hybrid operating space is established, characterized by a person's continuous intellectualized interaction with machine-activated information (Venda, 1990). The mentioned space is configured as a system based on an organized complexity defined by behaviorally non-random relationships between human actors, machines, and technological systems constantly changing (Khramov, 2020; Lavrov & Pasko, 2018) its transformation happens as a result of the operator's tasks change, data from the context within which he or she is embedded, and feedback returned by the AI-based system. These features enable the creation of a pro-active communication framework, i.e., an environment with the ability to process collected data and communicate feedback to the user (Sun, Li & Gou, 2023), through active tool learning that aims to improve human-computer interaction through a user prediction model (Senft et al., 2017; Cakmak, Chao & Thomaz, 2010) and considers diversity among different users, introducing the issue of personalization of intention. It is necessary to collect the information useful for optimization and improvement of the model and its parameters, to support the process and to design a proactive HMI system.

2.2. Contribution

The experimentation objective concerns the definition of a graphical language, a set of communication guidelines, and the design of an interface layer that interacts with existing established HMI systems and becomes a tool for transition from a Graphical User Interface designed for the control of the machine to an industrial process optimized for different forms of Human Machine collaboration. The operators then become the end-users of interface system and they are involved in the design-driven process of defining the graphical elements to address operational needs.

In this framework, it is possible to explore a mixed-initiative system in the industrial environment, i.e., systems in which a human and an agent collaborate to make decisions (Allen, Guinn, & Horvtz 1999; Chen & Barnes, 2014); the artificial agent must be designed with the following aspects into account: autonomy, responsiveness to the environment and the pursuit of goal-oriented behavior (Russell & Norvig, 2009; Wool-

dridge & Jennings, 1995). Bidirectional communication between humans and AI becomes a cooperative tool for monitoring and receiving pro-active feedback; the concept of pro-active in the context of HMI can be associated with the research area related to autonomy, which means "the ability to perform intended tasks based on current state and sensing without human intervention." (ISO, 2012).

To test this system, the development of this contribution will follow a collaborative process being started by collecting the needs of those working within this field through an exploration of the relationship between users, machines, and interfaces. The collection and clustering of the information obtained from the collaborative analysis will be useful in defining the design insights that will enable the definition of system characteristics. In fact, it is fundamental to identify the conceptual model of the user interface and visual language for the development of a prototype that can be tested through co-design activities.

The first two steps of mapping needs allow operators to be involved in the initial definition of insights, in order to consider operational needs for optimizing interaction and identify key aspects of the current interface used for machine management to identify the correct way to integrate the new system. It is significant to define the quantity and quality of information, according to operational activities; thus, it is possible to structure communication based on the transparency of shared feedback from artificial intelligence, so that operators can quickly identify and understand it (Billsus, Hilbert & Maynes-Aminzade, 2005). The definition of the technological model can be based on behavior and human reasoning, used to inform the AI model, which defines the work activities carried out during the production process; in fact, if the two agents share a common cognitive framework, it is possible to form a consistent mental expectation during the interaction (Chen & Barnes, 2014). The definition of the interaction model and graphic elements that will characterize the interface involves the creation of creating a system of elements that can integrate with existing SCM systems; this experimentation is characterized by an initial phase of identifying the graphic and digital experience-related components

and then developing a prototype, created through development tools such as Figma or Adobe XD, that can be tested through the inclusion of operators. The prototype aims to integrate with machine management interfaces while avoiding overlapping information, thus through graphical elements that distinguish the feedback provided by AI from other types of interactions; usability testing can occur, therefore, through the overlapping of a graphical and prototype level. The testing phase involves several levels:

- Accessibility and usability testing: testing of the elements and interaction modes with respect to the accessibility and usability of the selected elements with a group of end users;
- Interaction experience texting: testing related to the experience of interaction and integration with current SCM systems with a group of end users on a selection of activities defined by the research team, with a focus on evaluating the quantity and quality of information entered;
- Value testing: test evaluating the perceived value of the interface and relationship with the AI.

3. Virtual prototyping

3.1. State of the art

A virtual prototype is a computer-based representation or simulation of a physical product or a process. It allows for presentation, analysis, and testing across various stages of the life cycle, including designing, manufacturing, service, and recycling. Virtual Prototyping refers to the creation and testing of these prototypes (Wang, 2002). Virtual Prototyping encompasses a wide range of techniques and tools, enabling engineers to create virtual replicas of physical systems (Budinoff & Kramer, 2022). This approach allows for rapid, dependable, and repeatable analysis of physical phenomena by offloading complex time-intensive calculations to a computer. This digital approach offers several advantages in the realm of virtual model creation, including the minimization of efforts, the mitigation of risks during the analysis and testing stages,

the ability to plan for manufacturing, conduct simulations and analyses, and visualize various design possibilities without the need for costly physical reiteration (Aromaa, 2017; Bharath & Rajashekar, 2015).

Virtual Prototyping can be a solution to support early Human-Machine Interaction design in realistic contexts (Aromaa & Väänänen, 2016). Virtual Reality (VR) and Augmented Reality (AR) technologies play a pivotal role. Using VR and AR, Virtual Prototyping allows end-users to experiment with various design alternatives at the early stage of the design and provide feedback to the developers (Kim et al., 2011). This process is shown to make the development process shorter and make the product more likely to be accepted by the end-users.

Therefore, according to the definition of Wang et al. (Wang, 2002), a complete virtual prototype should include three main types of models:

- A 3D solid model;
- A human-product/system interaction model;
- Perspective test models (e.g., structural analysis, motion analysis, manufacturability evaluations).

These interconnected models are developed to virtually present, test, and analyze a product, a system, or even a process. Obviously, the composition of a virtual prototype will vary depending on its intended application, potentially encompassing only a subset of these models.

Virtual Prototyping is used for several applications in manufacturing industries and product development. It has been applied in aerospace (Bennet, 1997; Schabacker et al., 2006; Jian et al., 2018), automotive (Kulkarni et al., 2011; Reiter et al., 2014; Genius & Apvrille, 2016; Kim et al., 2016), medical (Bidanda & Bártolo, 2007), railroad (Marzano et al., 2012), and maritime (Chu et al., 2018) industries.

Recent research has highlighted the efficacy of Virtual Prototyping in enhancing the design and performance of complex systems, such as robotic work cells (Raffaeli et al., 2022) and production engineering (Hauf et al., 2017). Virtual Prototyping also serves as a tool in the designing of workplaces where humans and robots share working spaces, playing a crucial role

in the testing and analysis before the physical implementation, ensuring not only the safety of the environment but also enhancing the level of cooperation between human workers and robots (Di Marino et al., 2022).

3.2. Contribution

Virtual Prototyping offers a strategic tool for analyzing the impact of design choices, reducing time-to-market, and enhancing quality, which is essential for sustainable transformative factories. Virtual Prototyping also supports early Human-Machine Interaction design in the work cell scenario, ensuring optimal ergonomics and efficiency. Additionally, Virtual Prototyping may help reduce material waste and energy consumption by allowing the simulation and optimization of manufacturing processes before physical implementation, minimizing the environmental impact.

As regards the analysis of Human-Machine Interaction, Virtual Prototyping facilitates comprehensive analysis of human-machine interaction. Through simulations and leveraging Virtual Reality (VR) and Augmented Reality (AR), it is possible to evaluate ergonomic factors, assess user feedback, and optimize interface design to enhance usability, safety, and overall user experience.

The PoC of the virtual prototype will be instrumental, providing a crucial contribution in the following key domain of designing and managing the work cell:

- Design Optimization: this entails creating and refining human-machine interfaces (HMIs) within the work cell. Different workplace layouts, control mechanisms, and feedback systems can be simulated and thus virtually prototyped in order to optimize user interaction, ensuring intuitive operation and maximizing efficiency in the manufacturing environment;
- Safety Evaluation: this involves the evaluation of safety measures and hazard mitigation strategies within the work cell. Designers can simulate various scenarios to assess the impact of Human-Machine Interactions on worker safety, identifying potential risks, and implementing preventive measures before physical implementation;

- Training and Education: a platform for immersive training and education within the work cell may be provided. Through virtual simulations, operators and technicians will be able to familiarize themselves with complex equipment, learn proper operating procedures, and practice troubleshooting techniques in a safe and controlled environment;
- Predictive Maintenance: by simulating equipment performance and monitoring real-time data, predictive maintenance models can anticipate potential failures, schedule maintenance activities, and optimize equipment uptime, ensuring continuous operation and minimizing unplanned downtime.

Concluding, the PoC of the virtual prototype serves as a cornerstone in enhancing design, safety, training, maintenance, and sustainability aspects within the manufacturing work cell, aligning with the features of the sustainable and transformative Factories of the Future (FoF).

4. Industrial orchestration

4.1. State of the art

The vision of Industry 4.0 (I4.0) foresees the automatic and continuous reconfiguration of factory floors and production lines to adapt to evolving business goals. This includes the automatic re-arrangement of the production lines through collaborative robots, as well as the continuous reconfiguration, deployment, and monitoring of new industrial components (Lasi et al., 2014; Colombo, Karnouskos & Mendes, 2010).

This paradigm shift requires consolidating heterogeneous services on the same edge node, e.g., real-time control, machine learning algorithms, and high-speed data acquisition, each of them with different requirements (Cilardo et al., 2022). Hence, the concepts of Fog/Edge computing and mixed-criticality systems become strictly intertwined, and the whole factory floor can be seen as a mixed-criticality system, with each node running jobs with different levels of criticality, i.e., the designation of the level of assurance against failure needed for a system component (Burns & Davis, 2022).

Virtualization is seen as an enabling technology for the implementation of mixed-criticality components since it provides support for resource abstraction, partitioning, and multiplexing, consolidating multiple Operating Systems (OSes) on the same hardware (Heiser, 2011; Blackberry, 2021). However, critical components must often meet temporal requirements, and consolidating real-time and general-purpose systems on the same System-on-a-Chip (SoC) requires ad hoc solutions (Cinque et al., 2022). One drawback of software virtualization is the overhead that hinders the efficient usage of hardware resources. Therefore, over time several proposals have risen to mitigate the overhead, such as hardware-assisted virtualization or para-virtualization. In this perspective, lightweight virtualization technologies (e.g., containers) are gaining the limelight in industrial environments as a way to pack and deploy low-latency and bandwidth-efficient services with reduced overhead and higher scalability compared to classical hypervisor-based solutions (Morabito et al., 2018; Struhar et al., 2020; Cinque et al., 2019). Nevertheless, OS-level virtualization (i.e., containers) is known to suffer from a reduced degree of isolation compared to hypervisor-based virtualization; thus it cannot be seen as a panacea (Randal, 2020). Containers are also seamlessly integrated into orchestration systems (e.g., Docker Swarm,[1] Kubernetes,[2] Apache Mesos),[3] which fosters fully automated management.

Orchestration systems are distributed systems that provide the automatic placement, deployment, monitoring, and migration of the packaged software across the infrastructure, behaving as cloud operating systems that manage hardware resources while abstracting their use (Khan, 2017; Rodriguez & Buyya, 2019). They represent a valuable technology to manage softwarized industrial components and to allow the required flexibility and intent-driven reconfiguration. Mainstream solutions, such as Docker Swarm, Kubernetes, and Apache Mesos mentioned above, are mainly designed for cloud environments, where the presence of both resourceful nodes and workloads that do not require strict timing constraints can be assumed. As such, they do not take into account I4.0 requirements, such as managing potential heterogeneous environments, real-timeliness, and carrier-grade availability with reduced times to repair.

The usage of orchestration and lightweight virtualization technologies to build and manage applications with critical timing constraints represents a recent trend in the literature, which wants to take advantage of the scalability, flexibility, reconfigurability, increased reliability, reduction of costs, and consumption of resources. In this context, different solutions have been proposed for the orchestration of real-time containers. For example, RT-Kubernetes (Fiori, Abeni & Cucinotta, 2022) is a modified version of the Kubernetes orchestrator, which leverages the rt-cgroups interface for the deployment of real-time containers that relies on the hierarchical modification to SCHED_DEADLINE described in (Abeni, Balsini & Cucinotta, 2019) to schedule cgroups. An enhanced version of the Kubernetes scheduler and node agent, i.e., kubelet, makes use of an extended description of tasks to include real-time constraints. Similarly, the work of (Struhar et al., 2021) modifies Kubernetes to enable the deployment of both real-time and best-effort containers. The Kubernetes control plane is modified to allow both admission control and scheduling of real-time containers, while an RT-manager is deployed on each working node for performance evaluation. Real-time containers are implemented in the same way as RT-Kubernetes, and node performance is evaluated by analyzing both container-level and system-level metrics during orchestration. A modified version of OpenStack is proposed in (Cucinotta et al., 2021), where real-time containers have been integrated to foster the Network Functions Virtualization management for next-generation networks. In (Xi et al., 2015) Open-Stack is modified to integrate real-time Virtual Machines for Xen, using the compositional schedulability analysis. The work in (Szalay, Matray & Toka, 2022) presents an architecture for real-time Function as a Service (FaaS). The work aims to open cloud/edge computing infrastructures to time-critical applications, assuming functions running within containers. The proposed architecture formulates an analytical model considering the end-to-end latency of real-time request/response pairs, highlighting the im- portance of real-time communication. In addition, a partitioning algorithm is designed to minimize the number of used compute nodes. A Kubernetes-edge-scheduler is proposed in (Toka, 2021), which aims to enable reliability for edge appli-

cations through spare backup resources. The scheduler considers latency constraints of applications by extending the cluster scheduler with the awareness of a delay matrix. A latency-aware placement is presented in (Monaco, Gala & Fohler, 2023) which describes a Kubernetes-based fog layer architecture for industrial automation contexts. The proposal is latency-aware with regard to communication costs, aiming at reducing the amount of data transferred between sensing, computing, and actuating devices leveraging a greedy heuristic. Several extensions to Kubernetes are proposed in order to better deal with shared resources, such as cache and memory bandwidth, diving the resources in discrete bands, and resizing pod resources for a collaborative Quality of Service (QoS) reduction. In (Netto et al., 2017) Kubernetes is modified to offer automatic and transparent state replication. To this aim, the proposal integrates both services coordination and a leader election protocol. In (Barletta et al., 2022) it is presented RunPHI, a framework that proposes to integrate mixed-criticality containers into orchestration systems. The framework leverages the strong isolation provided by partitioning hypervisors while taking advantage of orchestration techniques, paving the way to easy deployment of critical workloads in edge/cloud environments, failure mitigation through migration, and full reconfigurability for workloads with isolation requirements.

For completeness, we mention K3s and K0s as efforts to make Kubernetes more lightweight. K3s is stripped down to have fewer dependencies, cloud provider integrations, and addons, packing all control plane components in a single binary, with the ability to disable some components. K0s is similar to K3s, with an in-cluster database and storage support, and specialized workload support for serverless functions and IoT applications. Despite this, such efforts do not provide evidence for real-time guarantees and criticality awareness.

4.2. Contribution

The orchestration pertains to the automation of the operations to be done when deploying, updating, adapting, and monitoring the software running in the industrial work cell. Orchestration operations are needed (i) each time the work cell is reconfigured with new machines entering the production and other

ones leaving, or (ii) when an anomalous situation occurs. This is in line with the vision of Industry 4.0 (I4.0) and reconfigurable manufacturing systems (RMSs) (Morgan et al., 2021) that foresee the automatic and continuous reconfiguration of factory floors and production lines to adapt to evolving business goals. This includes the automatic re-arrangement of the production lines through collaborative robots, as well as the continuous reconfiguration, deployment, and monitoring of new industrial components (Lasi et al., 2014; Colombo, Karnouskos & Mendes, 2010).

To realize a Proof-of-Concept to showcase orchestration operations, we can imagine the working cell to have a **heterogeneous set of computing nodes**, ranging from smart sensors and embedded devices on machines, specialized computers controlling robots, machines dedicated to supervision and GUI, and edge or cloud servers to offload demanding workload or digital twin components. To **boost reuse and sustainability**, we assume that each node can host (consolidate) more than one workload, as done in cloud computing settings. Hence, we can imagine a (virtual) Programmable Logic Controller (PLC) to be flexibly deployed side-by-side with a supervisory system (e.g., a SCADA) and a management GUI, even all on the same machine, disrupting the strictly layered architecture mandated by the Computer Integrated Manufacturing (CIM) pyramid (Yu, Xu, & Lu, 2015). However, this type of flexibility requires to run workloads with differentiated real-time and safety requirements on the same shared hardware, which is typical of Mixed-Criticality Systems (Burns & Davis, 2022), considering that each computing node can have different characteristics in terms of *its ability to assure a given performance to deployed workloads*.

We refer to such ability as **assurance**. A high assurance node is capable of co-hosting different applications, reducing the interferences among each other. This can be achieved by using specialized hardware (e.g., multi-processor systems on chip with dedicated real-time processors and accelerators) and software (e.g. the use of real-time virtualization solutions like partitioning hypervisors). On the opposite, a low assurance node might be characterized by commodity hardware and standard operating systems, not able to isolate workloads from each other. So, if a given application starts to exhibit

an erroneous behavior, consuming extra memory or CPU resources, a high assurance node will be able to confine the extra anomalous resources demand up to a given bound, while a low assurance node could compromise the correct functioning of co-located workloads.

Nodes are connected each other with **different networks**, both wired and wireless, with different characteristics, ranging from standard interfaces, such as ethernet and Wi-Fi, to industrial networks, such as ModBus or WirelessHART and Zigbee. This heterogeneity and the presence of wireless links helps to reconfigure the working cell when needed. The different types of networks exhibit a different behavior, again in terms of assurance. High assurance networks can provide bandwidth reservation or strict temporal behavior (e.g., time-driven multiple access) to nodes, hence assuring bounds to the transmission latency. On the opposite, low assurance networks use random access protocols which are efficient but cannot provide strict bounds to the transmission latency. The network is managed by software functions (such as routers and firewalls) that need to be deployed on machines as well by the orchestrator.

In this setting, the mission of the orchestrator is to find an optimal deployment of network functions and application functions, able to satisfy a set of requirements, such as (not exhaustive): (i) *criticality* of the function (the software controlling in real-time robotic harm or a virtual PLC is more critical than the GUI software), (ii) *timing* demands in terms of deadlines and latency, (iii) *energy consumption*, trying to consolidate the functions on a reduced set of nodes. Several new orchestration solutions have been proposed in the literature to meet especially real-time demand (Fiori, Abeni & Cucinotta, 2022; Struhar et al., 2021; Toka, 2021), however not taking into account the concept of assurance that we aim to introduce and not challenging them yet in realistic industrial settings with digital twins, which represent the novel aspects of our experimentation in this field.

4.2.1. ITALTEL's IoT and Network Orchestration Solutions

The availability of advanced IT solutions constitutes a fundamental enabler for a digitalized industrial context, in relation to production processes and the use of resources.

Italtel includes two frameworks among its assets to support the development of specific applications:

- Development framework for use cases in the Internet-of-Everything (IoE) environment;
- Framework for the standard-based development of a network resource orchestrator.

Both are particularly relevant for the research purpose.

Italtel IoT Platform application

The Italtel IoT Platform application, depicted in figure 2, is specialized in the collection of data from heterogeneous sources (CNC machines, PLCs, multiple sensors, etc.) and allows proactive control of devices and effective dialogue with factory and corporate ERP systems.

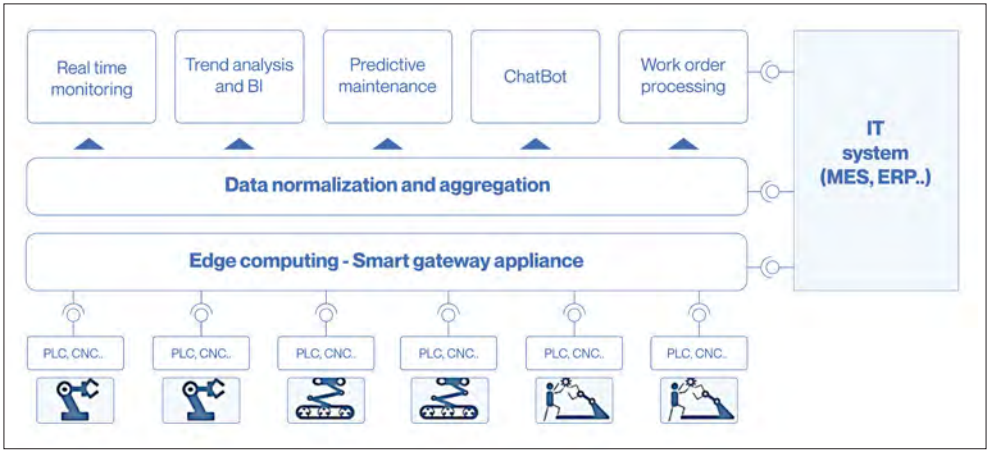
The application therefore carries out two simultaneous actions on the managed system:

- Acquisition of data from the peripheral devices, related analysis, and consequent definition of production KPIs;
- Reception of the directives from the ERP systems which are interpreted, translated, and sent to the PLCs of the industrial machines.

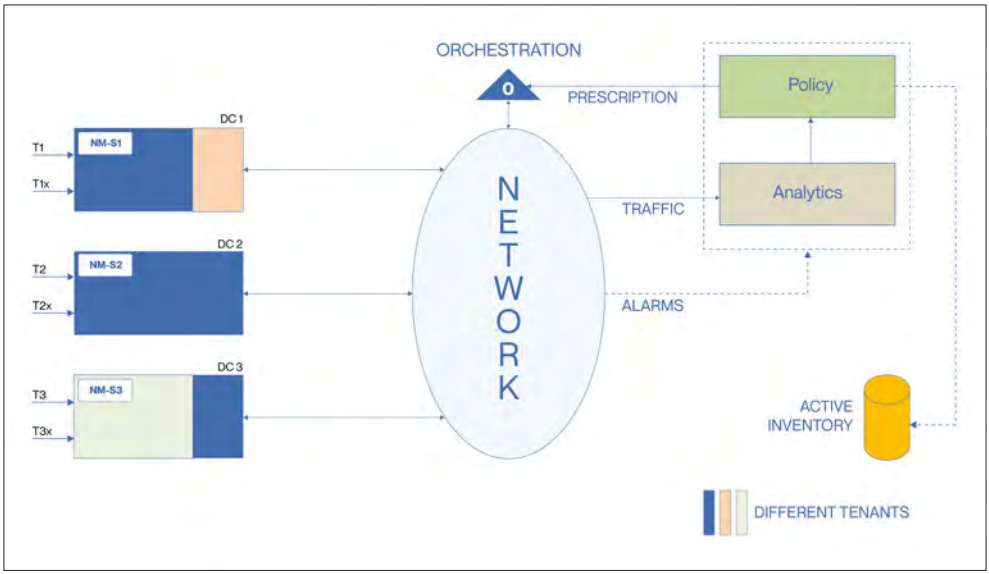
The platform, which is suitable for implementation in Edge and Fog Computing contexts, can be provided in "single node" mode, or on multiple nodes. Developed with microservices, it can be delivered in On Premises and Cloud mode.

The solution is designed to:

- Control and monitor the production line;
- Optimize production with related trend analysis;
- Improve production processes and reduce plant downtime.



2. ITALTEL's IOT
Platform application.



3. Network orchestrator
workflow.

Evolutionary aspects

The main evolution concerns the use of Machine Learning and Deep Learning for the HMI interface.

- *Real-time monitoring:* with the support of Artificial Intelligence (AI), the operator receives more comprehensive feedback regarding the functioning of the System and its status, rather than the values of individual sensors in a traditional interface.
- *Predictive maintenance:* AI-based procedures can identify situations of imminent criticality for the system, based on values measured by the sensors. This allows to intervene on the system in advance, limiting downtime and maintenance costs.
- *ChatBots:* use of natural language to implement commands towards PLCs and/or receive feedback from devices.

Italtel Network Orchestration Solution

A Network Services Orchestrator (NSO) is essential for the creation and management of a Network Service (for example Deep Packet Inspection (DPI), virtual private network VPN, DHCP, Firewall etc.) which, being composed of one or more Virtual Network Functions (VNF), requires constant monitoring of its life cycle.

The NSO is part of the implementation of Network Automation, an approach in which the network reacts autonomously to anomalous conditions, modifying its structure and preserving the regularity of operation as much as possible.

To create a network in Network Automation you need the following:

- Replacement of physical nodes with network services (NFV virtualization);
- Service Orchestration (NSO);
- Monitoring;
- Analysis of network conditions (Analytics);
- Intervention strategies (Intelligent Policy).

As depicted in figure 3, based on the conditions detected by the measurements on the network (monitoring) processed by the Analytics module and following the "prescriptions" of the Policy, the NSO mainly carries out the following actions:

- On-boarding of a VNF or a Network Service (NS);
- Creation, instantiation, scaling and termination of a VNF;
- Creation, instantiation, scaling and termination of a NS.

Notes

[1] Docker Inc. Swarm mode overview. https://docs.docker.com/engine/swarm/.
[2] The Linux Foundation. Kubernetes Home Page. https://kubernetes.io/.
[3] Apache Software Foundation. Apache Mesos Home Page. https://mesos.apache.org/.

References

Abeni, Balsini & Cucinotta, 2019
Abeni, L., Balsini, A., & Cucinotta, T. (2019). Container-based real-time scheduling in the Linux kernel. *ACM. Special Interest Group on Embedded Systems (SIGBED) Review*, *16*(3): 33–38. https://doi.org/10.1145/3373400.3373405

Allen, Guinn & Horvtz, 1999
Allen, J. E., Guinn, C. I., & Horvtz, E. (1999). Mixed-initiative interaction. *IEEE Intelligent Systems*, *14*(5), 14–23. https://doi.org/10.1109/5254.796083

Aromaa, 2017
Aromaa, S. (2017). Virtual prototyping in design reviews of industrial systems. In *Proceedings of the 21st International Academic Mindtrek Conference* (pp. 110–119).

Aromaa & Väänänen, 2016
Aromaa, S., & Väänänen, K. (2016). Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design. *Applied Ergonomics*, *56*, 11–18.

Barletta et al., 2022
Barletta, M., Cinque, M., De Simone, L., Della Corte, R., Farina, G., & Ottaviano, D. (2022). RunPHI: Enabling mixed-criticality containers via partitioning hypervisors in industry 4.0. In *2022 IEEE International Symposium on Software Reliability Engineering Workshops (ISSREW)* (pp. 134–135).

Bennett, 1997
Bennett, G. R. (1997). The application of virtual prototyping in the development of complex aerospace products. *Aircraft Engineering and Aerospace Technology*, *69*(1), 19–25.

Bharath & Rajashekar, 2015
Bharath, V. G., & Rajashekar, P. (2015). Virtual manufacturing: A review. In

National Conference Emerging Research Areas Mechanical Engineering Conference Proceedings (pp. 355–364).

Bidanda & Bártolo, 2007
Bidanda, B., & Bártolo, P. J. (Eds.) (2007). *Virtual prototyping & bio manufacturing in medical applications*. Springer Science & Business Media.

Billsus, Hilbert & Maynes-Aminzade, 2005
Billsus, D., Hilbert, D. M., & Maynes-Aminzade, D. (2005). Improving proactive information systems. In *Proceedings of the 10th International Conference on Intelligent User Interfaces* (pp. 159–166). https://doi.org/10.1145/1040830.1040869

BlackBerry, 2021
Blackberry Limited (2021). *Are hypervisors the answer to the coming silicon shortages?* (White Paper). https://blackberry.qnx.com/content/dam/blackberry-com/Documents/pdf/BlackBerry_QNX_Hypervisor_WhitePaper_22April2021_FINAL.pdf, 2021

Budinoff & Kramer, 2022
Budinoff, H., & Kramer, J. (2022). CAD as a virtual prototyping method: Uses and timing of computer-aided design artifacts in hardware design. *International Journal of Engineering Education*, *38*(6), 1747–1760.

Burns & Davis, 2022
Burns, A., & Davis, R. I. (2022). *Mixed criticality systems: A review* (13th ed.). Department of Computer Science, University of York.

Cakmak, Chao & Thomaz, 2010
Cakmak, M., Chao, C., & Thomaz, A. L. (2010). Designing interactions for robot active learners. *IEEE Transactions on Autonomous Mental Development*, *2*(2), 108–118. https://doi.org/10.1109/TAMD.2010.2051030

Chen & Barnes, 2014
Chen, J. Y. C., & Barnes, M. J. (2014). Human-agent teaming for multirobot control: A review of human factors issues. *IEEE Transactions on Human-Machine Systems*, *44*(1), 13–29. https://doi.org/10.1109/THMS.2013.2293535

Chu et al., 2018
Chu, Y., Hatledal, L. I., Zhang, H., Æsøy, V., & Ehlers, S. (2018). Virtual prototyping for maritime crane design and operations. *Journal of Marine Science and Technology*, *23*, 754–766.

Cilardo et al., 2022
Cilardo, A., Cinque, M., De Simone, L., & Mazzocca, N. (2022). virtualization over multiprocessor systems-on-chip: An enabling paradigm for the industrial internet of things. *IEEE Computer*, *55*(10), 35–47. https://doi.org/10.1109/MC.2022.3140896

Cinque et al., 2019
Cinque, M., Della Corte, R., Eliso, A., & Pecchia, A. (2019). Rt-cases: Container-based virtualization for temporally separated mixed-criticality task sets. In *Proceedings of 31st Euromicro Conference on Real-Time Systems (ECRTS 2019)* (pp. 5:1–22).

Cinque et al., 2022
Cinque, M., Cotroneo, D., De Simone, L., & Rosiello, S. (2022). Virtualizing mixed-criticality systems: A survey on industrial trends and issues. *Future Generation Computer Systems (FGCS)*, *129*, 315–330. https://doi.org/10.1016/j.future.2021.12.002

Colombo, Karnouskos & Mendes, 2010
Colombo, A.-W., Karnouskos, S., & Mendes, J.-M. (2010). Factory of the future: A service-oriented system of modular, dynamic reconfigurable and collaborative systems. In *Artificial Intelligence Techniques for Networked Manufacturing Enterprises Management* (pp. 459–481). Springer International Publishing.

Cucinotta et al., 2021
Cucinotta, T., Abeni, L., Marinoni, M., Mancini, R., & Vitucci, C. (2021). Strong temporal isolation among containers in OpenStack for NFV services. In *IEEE Transactions on Cloud Computing (TCC)* (pp. 99:1–1). https://doi.org/10.1109/TCC.2021.3116183

Di Marino et al., 2022
Di Marino, C., Rega, A., Vitolo, F., & Patalano, S. (2022). Enhancing human-robot collaboration in the industry 5.0 context: Workplace layout prototyping. In *International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing* (pp. 454–465). Springer International Publishing.

Ekbia & Nardi, 2014
Ekbia, H., & Nardi, B. (2014). Heteromation and its (dis)contents: The invisible division of labor between humans and machines. *First Monday*, *19*(6). https://doi.org/10.5210/fm.v19i6.5331

European Commision, 2018
European Commision. (2018). *Artificial Intelligence and Human Machine Interface (AI & HMI)*. https://s3platform.jrc.ec.europa.eu/artificial-intelligence-and-human-machine-interface-ai-hmi-#inline-nav-6

Fiori, Abeni & Cucinotta, 2022
Fiori, S., Abeni, L., & Cucinotta, T. (2022). RT-Kubernetes: Containerized real-time cloud computing. In *Proceedings of the 37th ACM/SIGAPP Symposium on Applied Computing* (pp. 36–39).

Fitts, 1951
Fitts, P. M. (1951). *Human engineering for an effective air-navigation and traffic-control system*. National Research Council.

Genius & Apvrille, 2016
Genius, D., & Apvrille, L. (2016). Virtual yet precise prototyping: An automotive case study. In *8th European Congress on Embedded Real Time Software and Systems (ERTS 2016)* (pp. 691–700).

Giaccardi & Redström, 2020
Giaccardi, E., & Redström, J. (2020). Technology and more-than-human design. *Design Issues*, *36*(4), 33–44. https://doi.org/10.1162/desi_a_00612

Hauf et al., 2017
Hauf, D., Süß, S., Strahilov, A., & Franke, J. (2017). Multifunctional use of functional mock-up units for application in production engineering. In *2017*

IEEE 15th International Conference on Industrial Informatics (INDIN) (pp. 1090–1095). IEEE, Emden, Germany.

Heiser, 2011
Heiser, G. (2011). Virtualizing embedded systems: Why bother? In *Proceedings of the 48th Design Automation Conference* (pp. 901–905). Association for Computing Machinery, New York.

Hoc, 2000
Hoc, J.-M. (2000). From human–machine interaction to human–machine cooperation. *Ergonomics*, *43*(7), 833–843. https://doi.org/10.1080/001401300409044

Ionescu, 2022
Ionescu, B.-I. (2022). *Design and implementation of human-machine interface and interaction in human-centered manufacturing systems* [Thesis for Master of Information and Communication Technologies]. https://doi.org/10.13140/RG.2.2.12903.52644

Jian et al., 2018
Jian, F. U., Jean-Charles, M. A. R. E., Liming, Y. U., & Yongling, F. U. (2018). Multi-level virtual prototyping of electromechanical actuation system for more electric aircraft. *Chinese Journal of Aeronautics*, *31*(5), 892–913.

Kent et al., 2021
Kent, L., Snider, C., Gopsill, J., & Hicks, B. (2021). Mixed reality in design prototyping: A systematic review. *Design Studies*, *77*(13). https://doi.org/10.1016/j.destud.2021.101046

Khan, 2017
Khan, A. (2017). Key characteristics of a container orchestration platform to enable a modern application. *IEEE Cloud Computing*, *4*(5), 42–48. https://doi.org/10.1109/MCC.2017.4250933

Khramov, 2020
Khramov, V. V. (2020). Development of a human-machine interface based on hybrid intelligence. *Modern Information Technologies and IT-Education, 16(4)*, 893–900. https://doi.org/10.25559/SITITO.16.202004.893-900

Kim et al., 2011
Kim, C., Lee, C., Lehto, M. R., & Yun, M. H. (2011). Affective evaluation of user impressions using virtual product prototyping. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *21*(1), 1–13.

Kim et al., 2016
Kim, B., Kashiba, Y., Dai, S., & Shiraishi, S. (2016). Testing autonomous vehicle software in the virtual prototyping environment. *IEEE Embedded Systems Letters*, *9*(1), 5–8.

Kulkarni et al., 2011
Kulkarni, A., Kapoor, A., Iyer, M., & Kosse, V. (2011). Virtual prototyping used as validation tool in automotive design. In *19th International Congress on Modelling and Simulation, Perth, Australia* (pp. 419–425).

Lasi et al., 2014
Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., & Hoffmann, M. (2014). Industry

4.0. *Springer Business & Information Systems Engineering (BISE)*, *6*(4), 239–242. https://doi.org/10.1007/s12599-014-0334-4

Lavrov & Pasko, 2018
Lavrov, E., & Pasko, N. (2018). Development of models for computer systems of processing information and control for tasks of ergonomic improvements. In R. Damaševičius & G. Vasiljevienė (Eds.), *Information and Software Technologies* (Vol. 920, pp. 98–109). Springer International Publishing. https://doi.org/10.1007/978-3-319-99972-2_8

Marzano et al., 2012
Marzano, A., Agyapong-Kodua, K., & Ratchev, S. (2012). Virtual ergonomics and time optimization of a railway coach assembly line. *Procedia CIRP*, *3*, 555–560.

Monaco, Gala & Fohler, 2023
Monaco, G., Gala, G., & Fohler, G. (2023). Extensions for shared resource orchestration in Kubernetes to support Rt-cloud containers. *arXiv*. https://doi.org/10.48550/arXiv.2301.07479

Morabito et al., 2018
Morabito, R., Cozzolino, V., Ding, A. Y., Beijar, N., & Ott, J. (2018). Consolidate IoT edge computing with lightweight virtualization. *IEEE network*, *32*(1), 102–111. https://doi.org/10.1109/MNET.2018.1700175

Morgan et al., 2021
Morgan, J., Halton, M., Qiao, Y., & Breslin, J. G. (2021). Industry 4.0 smart reconfigurable manufacturing machines. *Journal of Manufacturing Systems*, *59*, 481–506. https://doi.org/10.1016/j.jmsy.2021.03.001

Netto et al., 2017
Netto, H. V., Cheuk Lung, L., Correia, M., Luiz, A. F., & Moreira Sá de Souza, L. (2017). State machine replication in containers managed by kubernetes. *Elsevier Journal of Systems Architecture*, *73*. https://doi.org/10.1016/j.sysarc.2016.12.007

Nothdurft, Ultes & Minker, 2015
Nothdurft, F., Ultes, S., & Minker, W. (2015). Finding appropriate interaction strategies for proactive dialogue systems–An open quest. In *Proceedings of the 2nd European and the 5th Nordic Symposium on Multimodal Communication* (Vol. 110, pp. 73–80).

Parasuraman, Sheridan & Wickens, 2000
Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation. *IEEE Transactions on Systems, Man and Cybernetics-Part A: Systems and Humans*, *30*(3), 286–297. https://doi.org/10.1109/3468.844354

Raffaeli et al., 2022
Raffaeli, R., Neri, F., Peruzzini, M., Berselli, G., & Pellicciari, M. (2022). Virtual prototyping as a supporting tool for the design of complex robotic cells. In C. Rizzi, F. Campana, M. Bici, F. Gherardini, T. Ingrassia, P. Cicconi (Eds.), *Design Tools and Methods in Industrial Engineering II. ADM 2021. Lecture Notes in Mechanical Engineering* (pp. 675–682). Springer International Publishing.

Randal, 2020
Randal, A. (2020) The ideal versus the real: Revisiting the history of virtual machines and containers. *ACM Computing Surveys (CSUR)*, *53*(1):1–31.

Reiter et al., 2014
Reiter, S., Burger, A., Viehl, A., Bringmann, O., & Rosenstiel, W. (2014, March). Virtual prototyping evaluation framework for automotive embedded systems engineering. In *7th International ICST Conference on Simulation Tools and Techniques (SIMUTools)* (pp. 1–10).

Rodriguez & Buyya, 2019
Rodriguez, M. A., & Buyya, R. (2019). Container-based cluster orchestration systems: A taxonomy and future directions. *Wiley Software: Practice and Experience*, *49*(5), 698–719. https://doi.org/10.1002/spe.2660

Russell & Norvig, 2016
Russell, S. J., & Norvig, P. (2016). *Artificial intelligence: A modern approach* (3th ed.). Pearson.

Schabacker et al., 2006
Schabacker, M., Sabeur, M., & Vajna, S. N. (2006). INSIDES: A new design and simulation platform for virtual prototyping in automotive and aerospace industry. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 4255, pp. 1247–1254).

Senft et al., 2017
Senft, E., Lemaignan, S., Baxter, P. E., & Belpaeme, T. (2017). Leveraging human inputs in interactive machine learning for human robot interaction. In *Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction* (pp. 281–282). https://doi.org/10.1145/3029798.3038385

Sheridan & Verplank, 1978
Sheridan, T. B., & Verplank, W. L. (1978). *Human and computer control of undersea teleoperators*. Massachusetts Institute of Tech Cambridge Man-Machine Systems Lab.

Struhár et al., 2021
Struhár, V., Craciunas, S. S., Ashjaei, M., Behnam, M., & Papadopoulos, A. V. (2021). REACT: Enabling real-time container orchestration. In *Proceedings of 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (pp. 1–8). https://doi.org/10.1109/ETFA45728.2021.9613685

Sun, Li & Guo, 2023
Sun, X., Li, J. & Guo, W. (2023). A design approach of proactive hmi based on smart interaction. In T. Ahram, W. Karwowski, P. Di Bucchianico, R. Taiar, L. Casarotto, & P. Costa (Eds.), *Intelligent Human Systems Integration (IHSI 2023): Integrating people and intelligent systems. AHFE (2023) International Conference*. AHFE Open Access, Vol 69. AHFE International, USA. http://doi.org/10.54941/ahfe1002823

Szalay, Matray & Toka, 2022
Szalay, M., Matray, P., & Toka, L. (2022). Real-Time FaaS: Towards a latency bounded serverless cloud. *IEEE. Transactions on Cloud Computing (TCC)*.

Toka, 2021
Toka, L. (2021). Ultra-reliable and low-latency computing in the edge with kubernetes. *Journal of Grid Computing*, *19*(3), 31. https://doi.org/10.1007/s10723-021-09573-z

Venda, 1990
Venda, V. F. (1990). *Hybrid intelligence systems: Evolution, psychology, informatics*. Machine Engineering Industry - Mashinostroenie.

Wang, 2002
Wang, G. G. (2002). Definition and review of virtual prototyping. *J. Comput. Inf. Sci. Eng.*, *2*(3), 232–236.

Wooldridge & Jennings, 1995
Wooldridge, M., & Jennings, N. R. (1995). Intelligent agents: Theory and practice. *The Knowledge Engineering Review*, *10*(2), 115–152. https://doi.org/10.1017/S0269888900008122

Xi et al., 2015
Xi, S., Li, C., Lu, C., Gill, C. D., Xu, M., Phan, L. T. X., Lee, I., & Sokolsky, O. (2015). RT-Open Stack: CPU resource management for real-time cloud computing. In *Proceedings of 8th IEEE International Conference on Cloud Computing* (pp. 179–186). https://doi.org/10.1109/CLOUD.2015.33

Yu, Xu, & Lu, 2015
Yu C., Xu X., & Lu Y. (2015), Computer-integrated manufacturing, cyber-physical systems and cloud manufacturing concepts and relationships. *Manufacturing Letters*, *6*, 5–9. https://doi.org/10.1016/j.mfglet.2015.11.005

NOVEL OPERATOR-CENTRIC DIGITAL TECHNOLOGIES FOR A SUSTAINABLE INDUSTRIAL WORKPLACE

Francesca Calabrese, Marco Carricato*, Edoardo Idà*, Andrea Lucarini*, Roberto Meattini**, Maria Elena Nenni***, Gianluca Palli**, Alberto Regattieri*, Filippo Zoffoli**

1. Introduction

Industry 4.0 technologies are revolutionising industrial workplaces by advancing system and worker health management, enhancing Human-Machine Interaction, and enabling flexible manufacturing solutions. These innovations, underpinned by digital technologies, have their roots in predictive maintenance, reconfigurable and collaborative robotic systems, and AI-driven Human-Machine Interfaces, which are key enablers in creating sustainable, efficient, and adaptable production environments.

Predictive maintenance empowers production systems to become self-aware, self-predictive, self-configuring, and self-maintaining (Zonta et al., 2020). By equipping machinery with sensors that continuously monitor their condition, it is possible to detect early signs of faults, identify the specific type of fault, and predict the Remaining Useful Life (RUL) of equipment (Jardine, Lin & Banjevic, 2006). This proactive approach minimises downtime, optimises machinery longevity, and enhances overall efficiency. The collection of data from reconfigurable manipulation systems is crucial in this context, as it allows for the training, validation, and testing of data-driven approaches for diagnostics and prognostics in highly dynamic environments.

Integrating robotic manipulators with automatic production lines is crucial for achieving this flexibility, and deployability and reconfigurability are key enabling factors. Cable-driven Parallel Robots (CDPRs) offer a promising solution for reconfigurable and they have been proposed for various applications, including assisted or automated assembly (Pott, Meyer & Verl, 2010), high-rack warehouse storage and retrieval (Bruckmann et al., 2012), and palletising tasks (Marchesini, 2023). Optimising the performance of CDPRs involves selecting the appropriate

Authors are alphabetically listed

**Department of Industrial Engineering, Alma Mater Studiorum - University of Bologna, Italy*

***Department of Electrical, Electronic, and Information Engineering "Guglielmo Marconi", Alma Mater Studiorum - University of Bologna, Italy*

**** Department of Industrial Engineering, University of Naples Federico II, Italy*

sensors for calibration, estimation, or control, as small sensor errors can be amplified by the robot's transmission chain and control algorithms, leading to performance issues (Idà, Merlet & Carricato, 2019), (Gabaldo, Idà & Carricato, 2023). Digital prototyping tools dedicated to optimising the robot's mechatronic architecture—its geometry, inertia components, sensors, overall size, and installed power—are essential for enhancing the industrial involvement of CDPRs. These tools contribute to improved sustainability in reconfigurable automation, achieving levels of efficiency not possible with current solutions.

As automation becomes more prevalent, Human-Machine Interaction (HMI) become of interest, as understanding the factors that influence collaborative task quality and operator well-being is essential (Ayaz et al., 2012; Krugh & Mears, 2018). Automation changes human roles in complex ways, requiring a deeper understanding of human behaviour and environmental factors. Mental Workload (MWL), defined as the mental effort required to perform tasks, has been identified as a critical factor affecting productivity and task performance (Pacaux-Lemoine et al., 2022). The research underscores the importance of designing intelligent manufacturing systems that not only support human operators but also effectively manage MWL, thereby optimising working conditions. Addressing issues such as automation complacency and Out-Of-The-Loop (OOTL) performance is essential for improving working conditions through AI-enhanced human-machine collaboration.

Particularly, when dealing with collaborative robots, techniques such as kinesthetic teaching, where a human guides the robot to perform tasks, have been effective in addressing kinematic discrepancies (Billard et al., 2008). However, there is a growing need for more advanced human-robot interfaces that enable bidirectional information exchange during manual guidance. Technologies like motion capture systems, which track human kinematics, and haptic devices, which measure grip strength, are essential for enhancing this interaction (Häring, Bee & André, 2012; Walker, Zink & Mutschler, 2010). Additionally, surface electromyography (sEMG) has emerged as a valuable tool, providing real-time data that, when combined with machine learning and probabilistic modelling, enhances

programming by demonstration for collaborative robots (Meattini et al., 2018). The integration of these technologies facilitates more intuitive and effective human-robot collaboration, ultimately boosting productivity and work performance.

The paper describes some aspects of novel digital technologies developed in one of the PNRR PE 11 *Made in Italy Circolare e Sostenibile* (MICS) projects, to be integrated for the development of self-sustaining production systems, enhancing human-machine collaboration, and enabling the deployment of flexible, reconfigurable robotic solutions. These advancements are crucial for meeting the evolving demands of modern manufacturing, ensuring sustainability, and optimising overall system efficiency and performance. Section 1 deals with the Predictive maintenance aspect of the project, while Section 2 with reconfigurable robotic systems. Section 3 introduces the studied HMI Technologies, and Section 4 focuses on collaborative robots programming. In the end, the project's expected outcomes are highlighted.

2. Predictive maintenance

Predictive maintenance, as the most advanced strategy, utilises sensor-collected data to predict the future health behaviour of these systems. It involves early fault detection and the prediction of Remaining Useful Life (RUL), which denotes the time until failure (Jardine, Lin & Banjevic, 2006). These practices are crucial in the industrial field, aligning with economic and sustainability goals by preventing incorrect working conditions and unexpected breakdowns. They also enhance safety for operators, optimise component lifespan, and reduce scrap.

The Prognostics and Health Management approach to predictive maintenance includes collecting weak and noisy operational signals, extracting health-related information (feature extraction), and employing advanced Machine and Deep Learning models. These models establish connections between input parameters, health stages (fault detection and diagnostics), and RUL prediction (Lei et al., 2018).

Digitalisation and ICT technologies play a pivotal role in data collection, model development, and inference. Edge com-

puting, for instance, enables early fault detection and quick restoration of nominal functions by operators. It facilitates rapid extraction of pertinent information from raw signals, circumventing the time-consuming process of data transmission (Xu et al., 2021).

This approach empowers operators by providing real-time insights into equipment conditions, enabling prompt corrective actions and minimising downtime. Simultaneously, it reduces scrap rates, maintains productivity, and enhances spare parts management through improved forecasting of RUL (Zhuang et al., 2023).

Despite the promise of data-driven methods, practical implementation remains nascent due to challenges such as data availability and quality. While ideal conditions involve simulated and labelled data for all possible scenarios, complex systems present obstacles in fault simulation due to economic and safety concerns. Variations in working conditions further impact predictive accuracy, especially in reconfigurable systems designed for diverse tasks and environments (Calabrese et al., 2022).

Human-machine collaboration emerges as crucial in overcoming these challenges. It enables automated labelling of datasets using sequence classification and regression methods, while unsupervised deep learning models uncover novel behaviours and fault conditions. Operators contribute by defining these novel behaviours, ensuring their incorporation into diagnostic and prognostic model training.

In conclusion, while data-driven approaches hold immense potential, addressing practical challenges requires advancements in data acquisition, labelling techniques, and adaptive modelling.

3. Reconfigurable robotic systems

Cable-driven Parallel Robots (CDPRs) are a noteworthy highly-reconfigurable solution for large-scale operations. They are parallel-architecture robots characterised by many servo-actuated cables attached to a working platform in a parallel fashion and whose spooling on servo-winches displaces the platform in space. The workspace they can achieve is practically limited

only by the amount of cable that can be spooled by winches, and by just re-arranging how cables are connected to a shared End-Effector (EE), or a supporting frame, their properties may be conveniently changed. In addition, cables are optimally loaded structural components, thus able to withstand severe loads with negligible weights. Unlike existing market solutions, this project is developing a reconfigurable robot with flexibility, deployability, and adaptability in mind.

The project addresses several key challenges. The first challenge is achieving flexibility through deployability, enabling the robot to adapt to various tasks and conditions autonomously. Unlike traditional CDPRs with fixed frames, the proposed design aims to make the robot self-contained within the EE, with all winches and cable-guiding elements integrated into the moving part. This makes the EE bulkier but also easier to transport, operate, and store, which is essential for freeing up factory floor space. The second challenge is the automatic determination of the optimal robot installation for a given task, critical for tasks like painting flat surfaces of varying sizes and conducting inspections. This challenge involves two major problems: defining a set of tasks that the machine can interpret and developing a workspace computation algorithm to optimise the robot's structure based on performance. The third challenge focuses on automatic calibration to maintain high accuracy despite frequent robot assembly and disassembly. This involves developing a calibration procedure that operates without human intervention, using conventional sensors integrated for both control and calibration. The project will explore advanced sensor fusion techniques and nonlinear least square approaches to solve this problem, with the performance of automatic calibration compared to traditional, operator-assisted methods.

To address these challenges, the project will design and manufacture a demonstrator of the reconfigurable robotic system, focusing on its basic control functionalities. The methodology includes the integration of internal sensors for autonomous calibration, the development of a task interpretation system, and the creation of a control-aware workspace computation tool. The robot's performance will be tested computationally and experimentally, with tasks such as painting and inspection used to demonstrate the system's effectiveness.

4. HMI technologies

This research explores the complex relationship between Mental Workload (MWL) caused by automation and its effects on worker performance and well-being. By reviewing 426 papers published between 2003 and 2023, three key research areas emerged in the field of human-machine interfaces and MWL.

First, the assessment of MWL has evolved from traditional methods, such as the NASA Task Load Index, to more advanced approaches. Non-invasive electroencephalography (EEG) now stands out for measuring cerebral responses in the prefrontal cortex during tasks, providing a deeper understanding of MWL (Jin et al., 2022). This shift to sophisticated techniques reflects a broader trend in understanding the cognitive processes behind MWL.

Second, the research emphasises optimising task allocation between human operators and collaborative robots (cobots) to enhance productivity and worker well-being. Balancing workload is crucial to prevent cognitive overload and improve overall productivity while safeguarding worker health (Calzavara et al., 2023). Cobots play a critical role in this balance by taking over repetitive or physically demanding tasks, allowing human operators to focus on more complex, cognitively engaging activities.

Third, the focus shifts to real-time measurement and optimisation of workload capacity. Real-time physiological sensing technologies, integrated with Artificial Intelligence (AI), enable continuous monitoring of MWL. AI is particularly significant as it allows a shift from reactive to predictive MWL management, improving task quality and operator well-being (Thorpe, Nesbitt & Eidels, 2020). AI's real-time analysis and prediction of MWL open new possibilities for dynamic task allocation and personalised intervention strategies.

This research aims to contribute by advocating a proactive approach to managing MWL, highlighting the benefits of AI in MWL management, and advancing efforts to manage MWL effectively. A Proof-of-Concept (PoC) is being developed to demonstrate these ideas in practice. The PoC addresses specific user needs, such as robots creating optimal working conditions and understanding operators' abilities to complete tasks

effectively. The PoC will showcase an AI-based tool operating in three stages: real-time MWL assessment, MWL prediction, and tailored countermeasures with feedback.

Developing this PoC presents several challenges, particularly in measuring MWL accurately. A multi-faceted approach is proposed, combining physiological metrics like EEG and heart rate with subjective assessments such as the NASA Task Load Index. Data collection involves a two-stage experimental procedure—Calibration and Data Collection—to gather subjective, objective, and scenario data. This dataset will train AI tools, accounting for individual variations in MWL responses.

Data processing steps include preprocessing to correct artefacts, feature extraction using signal processing techniques, and MWL prediction through statistical and machine learning methods. Adaptation and feedback mechanisms will optimise MWL, with continuous recording and analysis of intervention effectiveness.

5. Collaborative robots programming

Collaborative robots are becoming essential across various sectors, demonstrating precise behaviours through kinesthetic teaching. Traditional methods struggle to adapt to modern robotic functionalities, prompting the development of augmented kinesthetic teaching to enhance bidirectional communication during manual guidance. The integration of wearable devices shows promise in real-time detection of human motor intentions, aiming for effective and intuitive robot programming. Advanced techniques, including machine learning, are targeted to align teaching approaches with operators' implicit knowledge, enhancing human-robot collaboration.

The AI-Based Collaborative Robots PoC focus on improving teaching methodologies, exploiting the integration of wearable and/or grounded devices, which shows promise in real-time detection of human motor intentions, aiming for effective and intuitive robot programming. Advanced techniques, including machine learning, are targeted to align teaching approaches with operators' implicit knowledge, enhancing human-robot collaboration. Initially, the primary objective is to investigate

and outline a framework for intuitive trajectory programming to assist operators in target activities. The framework comprises a robot manipulator capable of learning trajectories through manual guidance. Advanced interfaces measuring additional user inputs are connected to the system, and machine learning algorithms are employed to extract information from these interfaces. This enables the improvement of trajectory features through intention detection which is not possible with manual guidance alone.

This PoC aims to bridge the gap between traditional kinesthetic teaching and modern collaborative robotics needs. By integrating machine learning and possibly physiological signals for enhanced teaching, the platform empowers operators with intuitive interfaces. The goal is to develop a dynamic teaching approach that improves efficiency and effectiveness in industrial robotisation endeavours. Understanding user requirements is fundamental to advancing human-robot interaction with intuitive programming solutions for collaborative robots. Insights into workflows and tasks where improved human-robot interaction can be effective are considered, with validation conducted in agreement with user experience and selected workflows. Evaluating the framework involves metrics such as usability tests, questionnaires measuring the perceived intuitiveness of programming solutions, and collaborative robotic task success rates. These metrics will be collected through specific tests related to user responses in using the prototype collaborative system.

6. Expected results

The research focuses on integrating advanced digital technologies to enhance industrial systems, improve human-machine collaboration, and optimise overall efficiency. A critical component of this research is the application of predictive maintenance to extend the Remaining Useful Life (RUL) of equipment. By collecting sensor data from reconfigurable Cable-Driven Parallel Robots (CDPRs), the project will train and validate models to predict RUL and detect faults. This proactive approach will minimise downtime, enhance machinery longevity, and optimise overall efficiency. The reconfigurable CDPR system itself will be designed

to autonomously adapt to various tasks, including painting and quality control. The integration of advanced sensors and AI will facilitate automatic calibration and performance optimisation, allowing the robot to maintain high performance with minimal human intervention. A pivotal outcome is the development of a sophisticated AI-based tool for real-time Mental Workload (MWL) management. This tool will utilise real-time physiological sensing and advanced machine learning to proactively monitor and optimise MWL, fostering a human-centric approach that improves task performance and worker well-being. Additionally, the research will develop an intuitive teaching interface for collaborative robots, incorporating advanced user input and intention detection technologies. This interface will enhance trajectory programming and human-robot interaction, improving the efficiency and effectiveness of robotic operations.

Overall, the integration of AI, predictive maintenance, reconfigurable robotics, and advanced human-machine interfaces aims to create a comprehensive digital solution that manages MWL, predicts RUL, and advances human-robot collaboration. This holistic approach will demonstrate how these technological advancements collectively enhance productivity, optimise equipment lifespan, and support innovation in sustainable and adaptable production environments that strongly focus on workers' needs and well-being.

References

Ayaz et al., 2012
Ayaz, H., Shewokis, P. A., Bunce, S., Izzetoglu, K., Willems, B., & Onaral, B. (2012). Optical brain monitoring for operator training and mental workload assessment. *NeuroImage*, *59*(1), 36–47. https://doi.org/10.1016/j.neuroimage.2011.06.023

Billard et al., 2008
Billard, A., Calinon, S., Dillmann, R., & Schaal, S. (2008). Robot programming by demonstration. *Springer Handbook of Robotics* (pp. 1371–1394). Springer. https://doi.org/10.1007/978-3-540-30301-5_60

Bruckmann et al., 2012
Bruckmann, T., Lalo, W., Nguyen, K., & Salah, B. (2012). Development of a storage retrieval machine for high racks using a wire robot. In *Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 771–780). https://doi.org/10.1115/DETC2012-70684

Calabrese et al., 2022
Calabrese, F., Regattieri, A., Bortolini, M., & Galizia, F. G. (2022). Data-driven fault detection and diagnosis: Challenges and opportunities in real-world scenarios. *Applied Sciences (Switzerland)*, *12*(18), 9212. https://doi.org/10.3390/app12189212

Calzavara, Faccio & Granata, 2023
Calzavara, M., Faccio, M., & Granata, I. (2023). Multi-objective task allocation for collaborative robot systems with an Industry 5.0 human-centered perspective. *The International Journal of Advanced Manufacturing Technology*, *128*(1–2), 297–314. https://doi.org/10.1007/s00170-023-11673-x

Gabaldo, Idà & Carricato, 2023
Gabaldo, S., Idà, E., & Carricato, M. (2023). Pose-estimation methods for planar underactuated cable-driven parallel robots. In S. Caro, T. Bruckmann, & A. Pott (Eds.), *Cable-Driven Parallel Robots* (pp. 3–15). Springer. https://doi.org/10.1007/978-3-031-32322-5_1

Häring, Bee & André, 2012
Häring, M., Bee, N., & André, E. (2012). Studies on grounding with gaze and pointing gestures in human-robot-interaction. In *Proceedings of the International Conference on Social Robotics* (pp. 378–387). https://doi.org/10.1007/978-3-642-34103-8_38

Idà, Merlet & Carricato, 2019
Idà, E., Merlet, J. P., & Carricato, M. (2019). Automatic self-calibration of suspended under-actuated cable-driven parallel robots using incremental measurements. In P. Cardou, C. Gosselin, T. Bruckmann, & A. Pott (Eds.), *Cable-Driven Parallel Robots* (pp. 333–344). Springer. https://link.springer.com/chapter/10.1007/978-3-030-20751-9_28

Jardine, Lin, & Banjevic, 2006
Jardine, A. K. S., Lin, D., & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing*, *20*(7), 1483–1510. https://doi.org/10.1016/j.ymssp.2005.09.012

Jin et al., 2022
Jin, L., Qu, H., Pang, L., & Zhang, Z. (2022). Sensitive channel selection for mental workload classification. *Mathematics*, *10*(13), 2266. https://doi.org/10.3390/math10132266

Krugh & Mears, 2018
Krugh, M., & Mears, L. (2018). A complementary cyber-human systems framework for Industry 4.0 cyber-physical systems. *Manufacturing Letters*, *15*, 89–92. https://doi.org/10.1016/j.mfglet.2018.01.001

Lei et al., 2018
Lei, Y., Li, N., Guo, L., Li, N., Yan, T., & Lin, J. (2018). Machinery health prognostics: A systematic review from data acquisition to RUL prediction. *Mechanical Systems and Signal Processing*, *104*, 799–834. https://doi.org/10.1016/j.ymssp.2017.11.016

Marchesini, 2023
Marchesini. (2023, September 11). *Product website*. https://www.marchesini.com/en/machines-lines/c-fly

Martin et al., 2021
Martin, C., Fabritius, M., Stoll, J. T., & Pott, A. (2021). A laser-based direct cable length measurement sensor for CDPRs. *Robotics*, *10*(2), 60. https://doi.org/10.3390/robotics10020060

Meattini et al., 2018
Meattini, R., Benatti, S., Scarcia, U., De Gregorio, D., Benini, L., Melchiorri, C. (2018). An sEMG-based human-robot interface for robotic hands using machine learning and synergies. *IEEE Transactions on Components, Packaging, and Manufacturing Technology*, *8*(7), 1149–1158. https://doi.org/10.1109/TCPMT.2018.2799987

Pacaux-Lemoine et al., 2022
Pacaux-Lemoine, M. P., Berdal, Q., Guérin, C., Rauffet, P., Chauvin, C., & Trentesaux, D. (2022). Designing human–system cooperation in Industry 4.0 with cognitive work analysis: A first evaluation. *Cognition, Technology & Work*, *24*(1), 93–111. https://doi.org/10.1007/s10111-021-00667-y

Pott, Meyer & Verl, 2010
Pott, A., Meyer, C., & Verl, A. (2010). Large-scale assembly of solar power plants with parallel cable robots. In *Proceedings of ISR 2010 and ROBOTIK 2010* (pp. 1–6). https://ieeexplore.ieee.org/document/5756909

Thorpe, Nesbitt, & Eidels, 2020
Thorpe, A., Nesbitt, K., & Eidels, A. (2020). A systematic review of empirical measures of workload capacity. *ACM Transactions on Applied Perception (TAP)*, *17*(3), 1–26. https://doi.org/10.1145/3422869

Walker, Zink, & Mutschler, 2010
Walker, D. S., Zink, M., & Mutschler, E. (2010). User-controlled variable impedance teleoperation. In *Proceedings of the IEEE International Conference on Robotics and Automation* (pp. 5352–5357). https://doi.org/10.1109/ROBOT.2010.5509811

Xu et al., 2021
Xu, Y., Nascimento, N. M. M., de Sousa, P. H. F., Nogueira, F. G., Torrico, B. C., Han, T., Jia, C., & Rebouças Filho, P. P. (2021). Multi-sensor edge computing architecture for identification of failures short-circuits in wind turbine generators. *Applied Soft Computing*, *101*, 107053. https://doi.org/10.1016/j.asoc.2020.107053

Zonta et al., 2020
Zonta, T., da Costa, C. A., da Rosa Righi, R., de Lima, M. J., da Trindade, E. S., & Li, G. P. (2020). Predictive maintenance in the Industry 4.0: A systematic literature review. *Computers and Industrial Engineering*, *150*(August), 106889. https://doi.org/10.1016/j.cie.2020.106889

Zhuang, Xu & Wang, 2023
Zhuang, L., Xu, A., & Wang, X. L. (2023). A prognostic driven predictive maintenance framework based on Bayesian deep learning. *Reliability Engineering and System Safety*, *234*(October 2022), 109181. https://doi.org/10.1016/j.ress.2023.109181

LIFE BEYOND SPACE: RESPONSIBLE ADVANCED DESIGN FOR NEW BALANCES BETWEEN SPACE HABITATS AND THE HUMAN FACTOR

*Laura Succini**

1. Introduction

Designing habitats for Deep Space is considered a highly complex area of investigation, not only because it involves extreme and unfamiliar environments in which humans live under conditions never experienced in other domains, but also due to the multitude of international stakeholders, interdisciplinary approaches, and research centers engaged in the conceptualization, value chain development, and sustainment of livability for future inhabitants (Di Pippo, 2023; ESPI & CIFS, 2023).

The *New Space* economy is fundamentally reshaping the strategic assets that have historically characterized space exploration. Emerging policies within space programs now involve not only governmental agencies but also major private companies (European Investment Bank, 2019; Council of the European Union, 2024). Certainly, the planned decommissioning of the International Space Station in 2030, evolving geopolitical scenarios, and upcoming challenges are prompting, on the one hand, renewed visions of human presence on the Moon and crewed missions to Mars, and on the other, the expansion of the range of individuals able to undertake missions in Low Earth Orbit (LEO) (Leach, 2015; Rollock & Klaus, 2022; Peng et al., 2024). This shift in vision presents design, business, and research opportunities for emerging enterprises, commercial players, and diverse sectors within academia and professional practice (Meusburger et al., 2023).

As a result, design processes must increasingly address human factors, habitability, crew dynamics, the development of new in-orbit activities, the activation of new cooperative policies, and strategies for both material and immaterial sustainability (Van Ellen et al., 2023). These changes demand a rethinking of both the space habitat and crew well-being, as well

*Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy

as of the design process itself in terms of design accessibility and process sustainability.

As Meusburger and Bishop (2021b) emphasize, the inclusion of more numerous and diverse crews will place human factors and the experience of inhabiting space at the center of future design efforts. These concerns are echoed in NASA's assessments (Buckland et al., 2022), which recognize the risk of incompatibility between habitats and "new users" if proper attention is not paid to human well-being, performance, and the physiological limits of the body in microgravity and confined spaces. The socio-spatial and psychological dimensions of future users and crews must become part of the design requirements, focusing not merely on survival but on prosperity (Meusburger & Bishop, 2021b), and on fostering a more qualitative experience of interaction between space travelers and the space environment (Bannova, 2021; Dominoni & Quaquaro, 2023).

With regard to design accessibility, several questions are now being raised: How can this professional and entrepreneurial sector open itself more to cross-disciplinary contamination in order to design future space exploration experiences? To ensure sustainable competitiveness, how can we train designers capable of activating more collaborative design processes? And in such a complex domain, how can knowledge and know-how become more accessible and transdisciplinary?

At the international level, several initiatives are emerging in an effort to address these issues. For example, in 2021 the International Astronautical Federation (IAF) established a dedicated Space Habitat Committee, composed of experts from various disciplines, to investigate the challenges of space habitats through an interdisciplinary lens, with the goal of enabling not only survival but also well-being in such extreme environments (Meusburger et al., 2023).

Thus, the necessary ideas and solutions do not originate from a single field of expertise. In recent years, new educational and research programs have been launched at multiple levels—master's degrees, courses within architecture and design curricula, and interdisciplinary design labs—supporting the development of new skills and experiences. These initiatives aim to integrate engineering approaches with methodologies focused on human well-being and on activating meaningful relationships

between environment, user, and community (Caratelli, 2020; Yashar, 2023; Iacobo, 2024). These efforts are designed both to imagine, design, prototype, and test future scenarios, and to support the development of sustainable systems and technologies that facilitate human presence in deep space.

The sustainability of the design process itself, on the other hand, can be analyzed through two key dimensions:

- Material: related to design timelines, the use of energy- and resource-intensive tools, the selection and application of materials during concept development and product design, and the overall configuration of the habitats;
- Immaterial: referring on one side to the value of local knowledge and expertise, and on the other to the psycho-physical and sensorial aspects that must be considered throughout the design process.

In the first case, the complexity of the sector leads to high resource consumption throughout the design process. Achieving a final output typically requires multiple stages of both low- and high-fidelity prototyping, which will in turn influence digital modeling and production workflows. Furthermore, time itself plays a critical role: difficulties in effectively coordinating heterogeneous designers, tools, design concepts, and product developments not only extend the process but also make it more energy intensive.

In the second case, current challenges highlight the importance of small and medium-sized enterprises (SMEs) in driving innovation within the space sector (Council of the European Union, 2024), and therefore the significance of territorial relationships and the exchange of expertise across different fields. From a design standpoint, it becomes clear that in an environment defined as *Isolated, Confined, Extreme* (ICE), achieving a successful mission, both socially and operationally, requires focusing on the "extraordinary dependency on the habitat, its technological capability as well as the sociospatial framing, i.e, the elements of the built environment that form the boundaries for the social and individual activities taking place within the habitat." (Meusburger & Bishop, 2021a, p. 2).

2. Responsible Advanced Design for Deep Space

Within this evolving landscape, design can play a key role both as a mediator of knowledge and expertise (Celaschi, 2008), and in defining a design model capable of integrating established aspects of the sector with emerging visions and future needs. This enables the activation of an anticipatory, reflective, transformative, and collaborative learning process (Celi, 2015; Celaschi et al., 2019; Succini, 2023; Gianfrate, 2024), serving the next generation of designers and benefitting new users of deep space.

These elements are embodied in the research project *Beyond the Space Life: Digital Living Lab for Human Life*, led by the Advanced Design Unit at the University of Bologna, in collaboration with the Department of Mathematics at the same university and the company Thales Alenia Space Italia.

The project, embedded in a context of high cultural and social value—that of Made in Italy—aims to respond to ongoing changes by hybridizing the space sector supply chain (Cozzi, 2024) with the knowledge and know-how that characterize the Italian territory, stemming from other supply chains and from the design discipline. Design becomes the means by which this interaction is transformed into opportunities for developing high-value-added sustainable strategies.

The main goal of this study is to construct, through a responsible and advanced design approach (Succini et al., 2024a), a model of a *Space Digital Living Lab*, which, through the integration of digital tools and physical experimentation, supports future designers, Made in Italy entrepreneurs, and professionals in the field:

1. In creating, through tools and best practices, complementary forms of knowledge and collaboration to accelerate the emergence of design ideas in the early stages of space habitat design, and to foster open and responsible innovation processes in the development of systems and products.
2. In formulating a methodological process of advanced design to develop new orbital habitat configurations aligned with sustainability criteria, particularly immaterial sustainability.

3. In conceiving a digital system for dynamic configuration of space habitats, to be used during the conceptual phase, allowing for early consideration of crew well-being, spatial customization based on psycho-relational characteristics, and in-mission spatial flexibility.

The project does not aim to create an entirely new design model, but rather to redesign specific parts of the existing process used by Thales Alenia Space Italia (TASI), introducing targeted enhancements in the early stages of the company's design process. The goal is to make extreme space environments more accessible and familiar to a wider range of designers, while also making the relationships between the various stages of design, from initial ideas to concept, more dynamic and sustainable.

In fact, TASI is not only a partner in the project but also represents the applied case study through which explore the core themes of the research, investigate specific design processes, and test new strategies. With over 40 years of experience as one of the main actors in the space sector—and having built the majority of the pressurized modules of the International Space Station (ISS)—TASI brings consolidated know-how that can validate and support the actions and outputs of the project.

As previously noted, a wide variety of professional roles are involved in the design of a space habitat. Of particular interest to this study, especially in relation to TASI's design processes, are the professionals engaged in the early stages of the project—from ideation to conceptualization. These roles can be grouped into two main macro-clusters, each containing categories with distinct needs and objectives, as described in table 1:

Tab. 1. Professional profiles of interest in the research.

	Professional Profiles	Objectives
New Designers	Designers, architects, engineers, etc.	To become familiar with the space sector, acquire a more systemic understanding of its specific characteristics, explore best practices from outside domains, and experiment with combinations of design approaches for extreme environments
Current Industry Designers	*Strategic, Conceptual, and Human Factor Design Field*: Professionals working in systemic design, layout conceptualization, and human factors expertise	To streamline design and systemic processes for concept development
	Modeling and Immersive Reality Field: Professionals involved in system-product modeling and virtual reality simulation	To improve workflow pipelines in order to reduce development time and enhance user movement dynamics within the virtual environment

A common objective shared by all designers involved in the project is to establish stronger interconnections between the various stages of the process: knowledge acquisition, conceptualization, and immersive design experience.

To investigate in a multidisciplinary, anticipatory, and inclusive manner what is available on the market, the variety of international policies and visions, and the emerging needs related to increased attention to the well-being of future users, the applied research methodology is *Responsible Advanced Design* (RAD) (Succini, 2023; Succini et al., 2024b). RAD is employed as an analytical framework, a design attitude, and a guide for evaluating the impact of the various design strategies implemented. The factors of this approach are: *anticipation, reflexivity, inclusiveness, responsiveness, care, and transparency* (Succini, 2023; Succini et al., 2025), which are translated into:

- Design practices guided by an open innovation model, where all stakeholders are involved collaboratively and ethically;
- The dissemination of responsible knowledge through open and adaptable tools tailored to the type of designer and the research objectives;

- The development of new behaviors and sustainable processes through future-oriented design that anticipates the needs of both humanity and the planet;
- The application of technology with consideration for designer well-being and its role as an enabler for learning and increasing design accessibility.

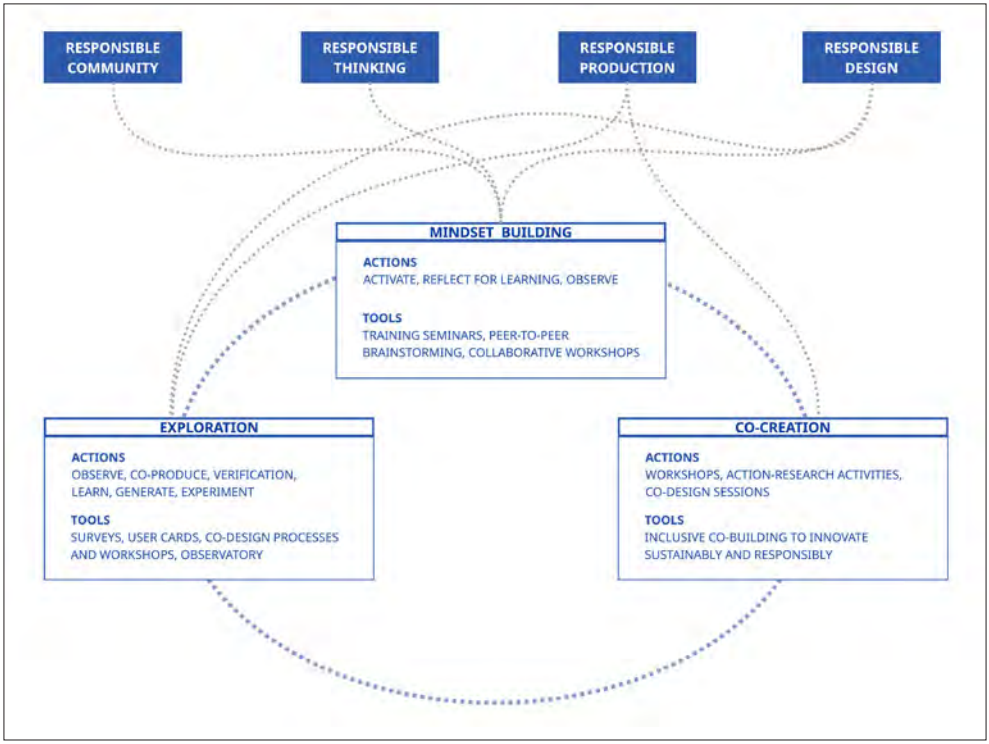
RAD is structured around macro-actions that translate the concept of responsibility across four key areas of design: *Responsible Design*, *Responsible Thinking*, *Responsible Production*, and *Responsible Community*. Each area is defined by a set of actions, insights, and design tools aimed at fostering responsible innovation (Stilgoe et al., 2013).

Given the highly interdisciplinary, multi-level, and multi-stakeholder nature of this context—along with strict design constraints such as safety and survival—the RAD methodology required integration, particularly in the knowledge and design phases, with both the Human-Centered Design approach (Norman & Draper, 1986; Long et al., 2022) and Human System Integration (NASA, 2010, 2014; Boy, 2021; Silvia-Martínez, 2023). This integration ensures the inclusion of human factors from the very beginning of the investigation and design process, not only addressing functional ergonomics but also psycho-perceptual dimensions.

In practical terms, RAD was articulated through three interconnected lines of action: *Mindset Building*, *Exploration*, and *Co-creation*. These areas are closely related, as certain actions are shared across them to achieve the project's objectives (see fig. 1). They also serve a dual purpose: first, to foster dialogue among project stakeholders and support collaborative design; second, to provide development and testing channels for the research's proof-of-concept outputs.

3. The design methodology applied to the TASI case

Each line of action was understood and employed both in the relationships among project partners and other system stakeholders, and as a set of tools and strategies used to define the project outputs.



1. Relationship between the Responsible Advanced Design approach and the three lines of action within the research project.
All images are reproduced in color in the online edition of the book.

3.1. Mindset building

Tools: Training seminars, peer-to-peer brainstorming sessions, collaborative workshops

Actions: Activation of flexible learning processes, construction of design responsibility, cross-disciplinary observation to foster change

Activating Collaborative Knowledge Within Working Groups

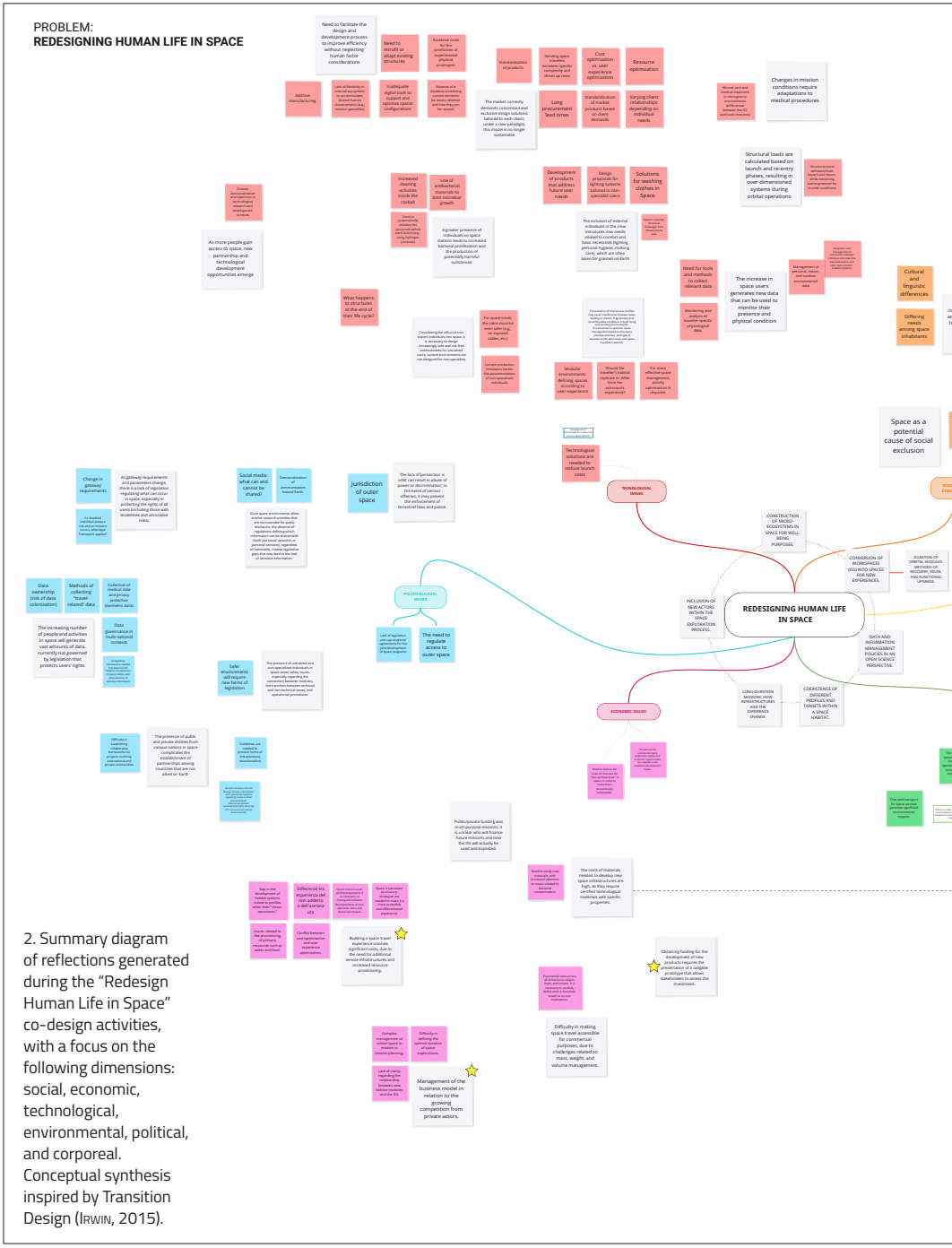
To foster a form of collective intelligence among the research team, a series of knowledge exchange and reflection activities took place between September 2023 and April 2024, focused on identifying values and critical issues to consider when redesigning human life in space.

These activities alternated between peer-to-peer training seminars, conducted by the project partners themselves, and collaborative brainstorming sessions. The seminars explored technical and engineering aspects of space habitats, the role of human factors in design, how training affects the psychological traits of crews and how design can enhance the experience of future users. These flexible learning formats allowed all participants to contribute and encouraged dialogue between academia and industry.

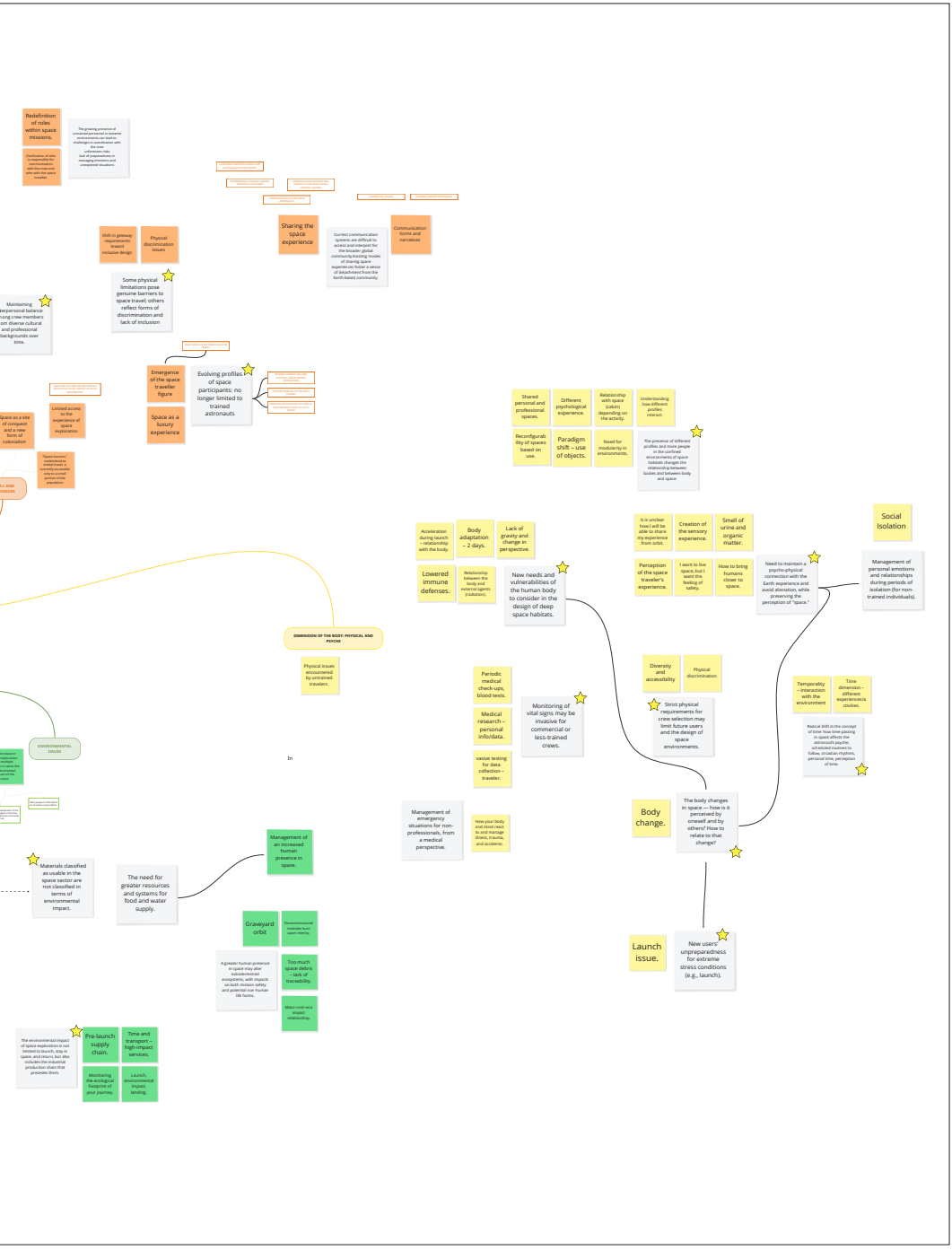
The brainstorming sessions, guided by the principles of Advanced Design and Transition Design (Zannoni et al., 2024), aimed to construct a shared vision of the future of life in space, examining the relationship between habitat, person, and community in scenarios more complex than those currently known. This challenge was analyzed through multiple dimensions: social, economic, technological, environmental, political, and corporeal.

The co-design activities engaged a broader group—including human factors experts, virtual reality specialists, researchers, engineers, and young designers—to reflect on the potential impacts of this transformation on people, policy, and communities in the medium and long term. Together, they identified a set of shared research *must-haves* to be considered throughout the project (see fig. 2). For example, the research was deliberately narrowed to focus on Low Earth Orbit, as designing for the Moon or Mars would require addressing a very different set of challenges.

The group's reflections extended beyond potential future users to include the evolving relationships between today's astro-



2. Summary diagram of reflections generated during the "Redesign Human Life in Space" co-design activities, with a focus on the following dimensions: social, economic, technological, environmental, political, and corporeal. Conceptual synthesis inspired by Transition Design (Irwin, 2015).


Redefinition of roles within space missions.
Clarification of roles is responsible for communication with the crew and who with the space traveller
The growing presence of commercial actors in space environments can lead to challenges in coordination with traditional actors.
This can increase risks, lack of preparedness in managing emotions and unexpected situations.
Sharing the space experience
Shift in gateway requirements toward inclusive design
Physical discrimination issues
Some physical limitations pose genuine barriers to space travel; others reflect forms of discrimination and lack of inclusion
Current communication systems are difficult to access and understand for the broader global community.Existing modes of sharing space experiences foster a sense of detachment from the Earth-based community.
Communication forms and narratives
Maintaining interpersonal balance among crew members can diverse cultural and professional backgrounds over time.
Emergence of the space traveller figure
Evolving profiles of space participants: no longer limited to trained astronauts
Space as a luxury experience
Limited access to the experience of space exploration
Space as a site of conquest and a new form of colonialism
"Space tourism," which is still an exhibit brand, is currently accessible only to small, wealthy population.
Shared personal and professional spaces.
Different psychological experience.
Relationship with space (cabin) depending on the activity.
Understanding how different profiles interact.
Reconfigurability of spaces based on use.
Paradigm shift – use of objects.
Need for modularity in environments.
The presence of different profiles and more people in the confined environments of space habitats changes the relationship between bodies and between body and space.
Acceleration during launch – relationship with the body.
Body adaptation – 2 days.
Lack of gravity and change in perspective.
Lowered immune defenses.
Relationship between the body and external agents (radiation).
New needs and vulnerabilities of the human body to consider in the design of deep space habitats.
It is unclear how I will be able to share my experience from orbit.
Creation of the sensory experience.
Smell of urine and organic matter.
Perception of the space traveller's experience.
I want to live space, but I want the feeling of safety.
How to bring humans closer to space.
Need to maintain a psycho-physical connection with the Earth experience and avoid alienation, while preserving the perception of "space."
Social Isolation
Management of personal emotions and relationships during periods of isolation (for non-trained individuals).
DIMENSION OF THE BODY: PHYSICAL AND PSYCHE
Physical issues encountered by untrained travelers.
Periodic medical check-ups, blood tests.
Medical research – personal info/data.
wasive testing for data collection – traveler.
Monitoring of vital signs may be invasive for commercial or less-trained crews.
Diversity and accessibility
Physical discrimination
Strict physical requirements for crew selection may limit future users and the design of space environments.
Temporality – interaction with the environment
Time dimension – different experiences/activities.
Radical shift in the concept of time: how time passing in space affects the astronaut's psyche; disorientation, altered follow, circadian rhythms, personal time, perception of time.
Body change.
The body changes in space — how is it perceived by oneself and by others? How to relate to that change?
Management of emergency situations for non-professionals, from a medical perspective.
How your body and mind react to and manage illness, trauma, and accidents.
Launch issue.
New users' unpreparedness for extreme stress conditions (e.g., launch).
ENVIRONMENTAL ISSUES
In
Management of an increased human presence in space.
The need for greater resources and systems for food and water supply.
Materials classified as usable in the space sector are not classified in terms of environmental impact.
Graveyard orbit
Too much space debris – lack of traceability.
A greater human presence in space may alter the surrounding ecosystems, with impacts on both mission safety and potential non-human life forms.
Macro-cosm-eco impact relationship.
The environmental impact of space exploration is not limited to launch, stay in space, and return, but also includes the entire production chain that precedes them.
Pre-launch supply chain.
Time and transport – high-impact services.
Monitoring the ecological footprint of your journey.
Launch, environmental impact, landing.

nauts and new crew members, and how these dynamics might influence habitat design and the types of activities that will take place within space stations.

In parallel, through desk research and collaborative workshops, the team explored the astronaut's life in orbit from an experiential perspective. Drawing on both scientific and divulgative sources, a journey map of the current astronaut was developed, highlighting their interactions with the environment, needs, and daily activities. This representation became the foundation for a collaborative analysis and reflection process, through which additional feedback, implicit actions, current pain points, and future insights emerged areas where design can intervene to begin imagining who the next users might be and what their more implicit needs could look like (fig. 3).

Building a new design mindset

The interaction between academia, industry, and various disciplines made it possible to identify the difficulties that new designers may face when approaching such an extreme design domain, as well as the concerns of seasoned professionals in the field toward less conventional design approaches. This ongoing dialogue between domain and out-of-domain led to the adoption of one of the core action areas of Advanced Design—*Extreme Design* (Celaschi, 2018)—not only as a direction for innovating products and systems, but also as a channel for exchange and advancement within the research framework.

As defined by Celaschi (2016), *Extreme Design* encourages designers to look beyond their immediate disciplinary boundaries to discover "stimuli for change" (p. 68). In this phase of the research, it played a key role in shaping the interaction dynamics between future designers, current professionals in the field, and the processes of knowledge-building and project development for the space sector.

Relationships between different domains were outlined to make this interaction more inclusive and interdisciplinary:

- Field observation linked to gaming experiences;
- Scenario-building for short, medium and long-term futures connected to anticipation and future studies;



3. Collaborative construction of the astronaut's journey map.

- Innovation in product-service systems aligned with open innovation models;
- Validating ideas through physical prototypes in dialogue with virtual or mixed reality.

These relationships and needs are part of the project's overarching goals and, as we will see in the next intervention line, have been explored through several practical experiments.

3.2. Exploration

Tools: Questionnaires, user profiling templates, co-design processes and workshops, observatory

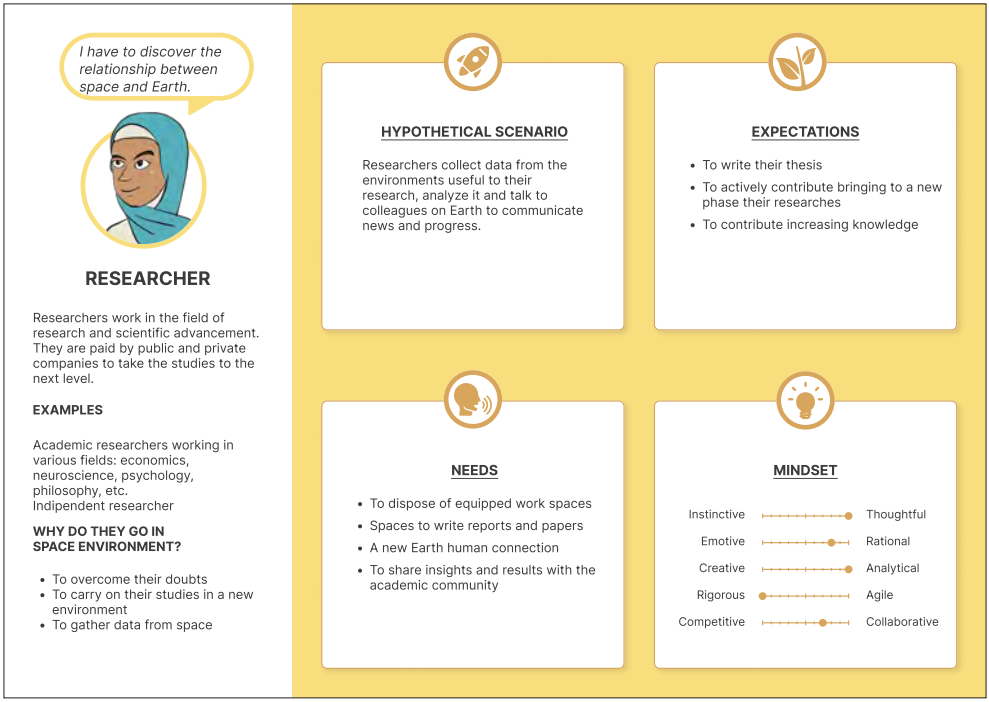
Actions: Observe to innovate, co-produce future scenarios and processes, validate through collective experimentation, learn digitally and in the field, generate new ideas, and test new formats of knowledge and design

Building a shared, sustainable, and open imagination for space exploration

Before identifying trends, relationships, and interdependencies that may arise within future habitats, it was first necessary to imagine who the potential users of near- and long-term space stations might be. The process of creating these archetypes was collaborative and open to public participation. The initial tools used were a future user profiling template and research based on scientific and divulgative sources. Cross-referencing primary data collected from TASI experts with secondary data led to the creation of initial proto-personas, which were later refined through an open questionnaire distributed to the digital community.

This approach resulted in the creation of nine archetypes, each with specific goals, expectations, and needs. These include: the Pioneer, the Researcher, the Artist, the Designer, the Mission Specialist, the Patient, the Space Traveler, the Content Creator, and the Station Manager (fig. 4).

This continuous exchange between internal and external perspectives highlighted several insights about potential future users: increased need for private personal spaces, the development of new work and leisure activities, and the requirement for dedicated workspaces, among others.



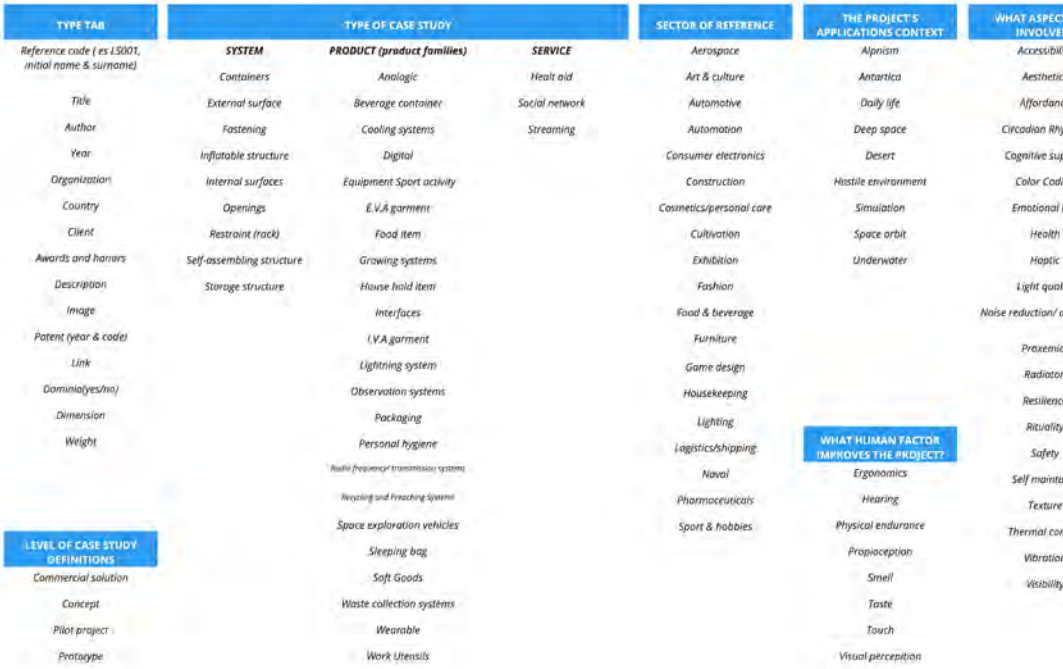
4. An example of a user archetype profile developed through the various research activities (image elaborated by Luigi Vella).

The exploration phase concerning the composition of future crews was accompanied by the observation and collection of products, concepts, services, best practices, and methodologies, both within the domain and from other extreme environments and adaptive experiences attentive to relational factors. The focus on lived experiences made it possible to center attention on the user as a person composed of both physical and emotional dimensions, and to view products and spaces as points of interaction.

This analysis led to the development of a case study cataloging template designed to be accessible and understandable to a wide community of designers (fig. 5). It became the foundation for formulating the advanced design methodology used to develop new habitat configurations, as described in the following paper.

Lastly, several formats for collaborative workshops were designed with the aim of:

- Validating the initial research findings (archetypes, actions, and needs) with designers and industry experts;



5. Basic cataloging template for case studies within the domain, outside the domain, and for methodological best practices.

- Building a cross-disciplinary design mindset related to extreme environments, informed by the contributions of professionals with different backgrounds and knowledge bases;
- Learning, designing, and validating through action-in a "learning by doing" mode.

An example of the latter is the *Space Workshop* held in April 2024, which involved 25 young designers and researchers (with backgrounds in product design, service design, and anthropology) guided by the project team and company representatives. In the first phase, participants approached the design domain through a virtual reality–guided gamified experience, which allowed them to observe and inhabit the environment, identify challenges, and collaboratively analyze them through co-design sessions (fig. 6).

The second phase, dedicated to conceptualization, introduced new users, new factors related to psycho-physical well-being, and new actions to consider within future habitats. This led



to initial reflections on design solutions that take into account these emerging users and the evolving spatial and relational affinities within space habitats.

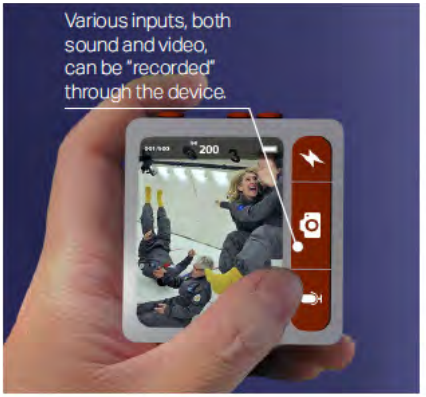
Building knowledge through a sustainable observatory

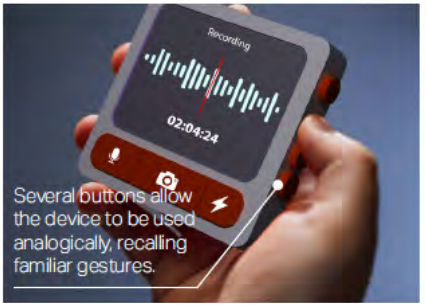
The various learning, validation, and collaborative design actions converged in the creation of an observatory model, drawing inspiration from the ADU experience (Celaschi et al., 2021) and reinterpreting it in the form of a new tool: the *Sustainable Innovation Observatory for Life Beyond Earth*. This digital space is designed to support designers in acquiring knowledge and developing new concepts, while also offering design strategies from an open innovation perspective. Its specific domains are:

- Far Future: offering long-term projections and visions to anticipate future challenges (Formia, 2017);
- Extreme Design: activating cross-fertilization between sectors and transferring knowledge across fields to promote sustainable innovation (Succini et al., 2024);



6. Space Workshop: learning process and early development of meta-design concepts (concept memory theme of Bastoni, Bologna, Fabbretti, Faceto, Pasini).







- Shelf Innovation: using the repository as a source of design projects and semi-finished solutions ready to be improved and adapted to meet emerging market needs (Celaschi, 2016).

3.3. Co-creation

Tools: Workshops, action research activities, co-design sessions
Actions: Inclusive co-construction for sustainable and responsible innovation

The final line of action focused on experimenting with the various tools and fine-tuning the proofs of concept.

The objectives of these ongoing or planned experiments—at different scales of the project—can be summarized as follows:

- Developing a multi-stakeholder action research protocol that uses the observatory as an initial learning tool and, subsequently, as a launchpad to expand future space habitat scenarios, stimulate new supply chains, and foster new collaborations;
- Activating continuous innovation processes that, through interaction between academia, young designers, and entrepreneurial players, can scale design processes from Earth to space—and vice versa—enhancing their sustainability;
- Facilitating interaction between product prototypes and the digital system for dynamic habitat configuration. The conceptualized products are intended to become a bridge between the virtual model, the initial strategic design process (users and needs), and the first touchpoints related to user well-being and spatial flexibility;
- Emphasizing designer responsibility;
- Creating synergies between the systemic design processes used during the ideation phase by TASI, the design-driven systems developed through this research, and TASI's own digital simulation systems (a topic explored in the next paper).

4. Conclusions: Space as an extreme context for rethinking terrestrial design practices

The aim of this research project is not to define a perfect, standardized solution to universally improve the well-being of future

space habitat users or the learning paths of future stakeholders in the field. Rather, it seeks to propose a more interdisciplinary and contamination-friendly approach to design open to both domain and out-of-domain inputs. "Thus, it is apparent that the human is the most fragile and variable element in the system" (Meusburger & Bishop, p. 180), and each person reacts and perceives extreme, confined conditions differently. However, enabling a degree of spatial variability, even through small product systems or experiential adjustments, can support adaptation and prosperity in extraterrestrial environments.

For designers or entrepreneurs, confronting constraints far beyond their usual scope—such as limited mobility, zero gravity, breathable air confined to enclosed systems, or lack of access to resources beyond those already present in the station—forces a shift in design approach. It calls for a focus on factors of survival, uncertainty, emotional response, and well-being, while imagining what cannot yet be experienced firsthand. This design mindset can also be transferred to other temporary or permanent extreme or confined contexts (Inglese et al., 2024).

In fact, the research is now expanding to address additional aspects: designing for the space sector through an open innovation model rooted in sustainability and Made in Italy know-how (from both space and non-space sectors) is revealing strategies and experimental approaches that may be transferable to other complex challenges on Earth, such as those stemming from natural disasters (floods, desertification, etc.) or other emerging crises.

References

Bannova, 2021
Bannova, O. (2021). Space architecture: Human habitats beyond planet earth. DOM publishers.

Boy, 2021
Boy, G. A. (2021). Human systems integration and design. In G. Salvendy & W. Karwowski (Eds.), *Handbook of Human Factors and Ergonomics* (5th ed., pp. 38–54). John Wiley & Sons, Inc.

Buckland et al., 2022
Buckland, D., Parisi, M., Mctigue, K., Wu, S.-C., Panontin, T., Vos, G., Petersen, D., & Vera, A. (2022). NASA's identified risks of adverse outcomes due to inadequate human systems integration architecture in human spaceflight. In *13th*

International Conference on Applied Human Factors and Ergonomics (AHFE 2022). https://doi.org/10.54941/ahfe1001427

Caratelli, 2020
Caratelli, P. (2020). Space architecture: The rise of a new discipline in architecture and design curricula. In: T. Ahram, R. Taiar, S. Colson, A., Choplin (Eds.), *Human Interaction and Emerging Technologies: Proceedings of the 1st International Conference on Human Interaction and Emerging Technologies (IHIET 2019)* (Vol. 1018, pp. 98–104). Springer. https://doi.org/10.1007/978-3-030-25629-6_16

Celaschi, 2008
Celaschi, F. (2008). Design come mediatore tra bisogni. In C. Germak (Ed.), *L'uomo al centro del progetto* (pp. 40–52). Allemandi.

Celaschi, 2016
Celaschi, F. (2016). *Non industrial design: Contributi al discorso progettuale*. Sossella.

Celaschi, Formia & Franzato, 2018
Celaschi, F., Formia, E., & Franzato, C. (2018). Ritorno al futuro. Il fattore tempo e i futures studies nell'approccio design driven all'innovazione. *Diid — Disegno Industriale Industrial Design*, *18*(64), 126–133.

Celaschi, Formia & Vulpinari, 2021
Celaschi, F., Formia, E., & Vulpinari, O. (2021). FutureDesignEd "Innovation in Design Education – Innovation in Education by Design". Permanent Observatory. In A. Bosco & S. Gasparotto (Eds.), *Updating Values. Perspectives on Design Education* (pp. 14–25). Quodlibet.

Celaschi et al., 2019
Celaschi, F., Formia, E., Iñiguez Flores, R., & León Morán, R. (2019). Design processes and anticipation. In R. Poli (Ed.), *Handbook of Anticipation: Theoretical and Applied Aspects of the Use of Future in Decision Making* (pp. 773–793). Springer International Publishing. https://doi.org/10.1007/978-3-319-91554-8_48

Celi, 2015
Celi, M. (2015). *Advanced design cultures*. Springer.

Cozzi, 2024
Cozzi, E. (2024). *Geopolitica dello spazio. Storia, economia e futuro di un nuovo continente*. Il Saggiatore.

Consiglio dell'Unione Europea, 2024
Consiglio dell'Unione Europea (2024). *Rafforzare la competitività dell'Europa grazie allo Spazio*. https://data.consilium.europa.eu/doc/document/ST-10142-2024-INIT/it/pdf

European Investment Bank, 2019
European Investment Bank (2019). *The future of the European space sector: How to leverage Europe's technological leadership and boost investments for space ventures*. Publications Office. https://data.europa.eu/doi/10.2867/484965

European Space Policy Institute, & Copenhagen Institute for Future Studies, 2023
European Space Policy Institute, & Copenhagen Institute for Future Studies

(2023). *Future of Space Exploration: Strategic Scenarios for European Space Exploration 2040-2060*. CIFS. https://www.espi.or.at/wp-content/uploads/2025/02/Future-of-European-Space-Exploration_final-version-7.pdf

Di Pippo, 2023
Di Pippo, S. (2023). *Space economy: The new frontier for development*. EGEA S.p.A. - Bocconi University Press.

Dominoni, 2021
Dominoni, A. (2021). *Design of supporting systems for life in outer space: A design perspective on space missions near earth and beyond*. Springer International Publishing. https://doi.org/10.1007/978-3-030-60942-9

Dominoni & Quaquaro, 2023
Dominoni, A., & Quaquaro, B. (2023). *Le città dell'universo: come sarà abitare nello spazio*. Il Saggiatore.

Formia, 2017
Formia, E. (2017). *Storie di futuri e design: Anticipazione e sostenibilità nella cultura italiana del progetto*. Maggioli.

Formia, Gianfrate & Succini, 2023
Formia, E. M., Gianfrate, V., & Succini, L. (2023). *Design per l'Innovazione Responsabile. Guida per processi formativi in trasformazione*. Franco Angeli.

Gianfrate, 2024
Gianfrate, V. (2024). *Innovare la città dei Servizi. Co-design responsabile, inclusivo, sostenibile*. Allemandi.

Häuplik-Meusburger, & Bishop, 2021a
Häuplik-Meusburger, S., & Bishop, S. (2021a). Habitats for our future extraterrestrial homes – Lessons from terrestrial analogues and our first habitats in space. In *50th International Conference on Environmental Systems (ICES, 2021)*.

Häuplik-Meusburger, & Bishop, 2021b
Häuplik-Meusburger, S., & Bishop, S. (2021b). *Space habitats and habitability: Designing for isolated and confined environments on earth and in space*. Springer International Publishing. https://doi.org/10.1007/978-3-030-69740-2

Häuplik-Meusburger et al., 2023
Häuplik-Meusburger, S., Maiwald, V., Perino, M. A., Bannoca, O., & Patarin-Jossec, J. (2023). The multidisciplinary world of space habitation design. *Room The Space Journal of Asgardia*, *33*, 30–37. https://room.eu.com/article/the-multidisciplinary-world-of-space-habitation-design

Iacobo, 2024
Iacobo, M. (2024). *Designing for outer space*. Mit News. https://news.mit.edu/2024/designing-outer-space-0623

Inglese, Lucibello & Rotondi, 2024
Inglese, G., Lucibello, S., Rotondi, C. (2024). Resilience envelopes: The "Fourth Environment" as a source of inspiration, a place for speculation and a territory for experimenting with new models of life. In C. Gambardella (Ed.), *For Nature/With Nature: New Sustainable Design Scenarios* (pp. 1039–1060). Springer. https://doi.org/10.1007/978-3-031-53122-4_60

Irwin, 2015
Irwin, T. (2015). Transition design: A proposal for a new area of design practice, study, and research. *Design and Culture*, 7(2), 229–246. https://doi.org/10.1080/17547075.2015.1051829

Leach, 2014
Leach, N. (2014). *Space architecture: The new frontier for design research*. Wiley.

Long, Cummaford & Stork, 2022
Long, J., Cummaford, S. and Stork, A. (2022). *HCI design knowledge: Critique, challenge, and a way forward*. Springer International. https://doi.org/10.1007/978-3-031-79209-0.

NASA, 2010
NASA (2010). *Human integration design handbook* (NASA/SP-2010-3407).

NASA, 2014
NASA (2014). *Human integration design handbook (HIDH)* (NASA/SP-2010-3407/REV1). NASA. https://www.nasa.gov/wp-content/uploads/2015/03/human_integration_design_handbook_revision_1.pdf

Peng, Kou & Chen, 2024
Peng, K.-L., Kou, I. E., & Chen, H. (2024). Space tourism value chain: When east meets west. *Springer Nature Singapore*. https://doi.org/10.1007/978-981-97-1606-7

Rollock & Klaus, 2022
Rollock, A. E., & Klaus, D. M. (2022). Defining and characterizing self-awareness and self-sufficiency for deep space habitats. *Acta Astronautica*, *198*, 366–375. https://doi.org/10.1016/j.actaastro.2022.06.002

Silva-Martinez, Etchells & Bradshaw, 2023
Silva-Martinez, J., Etchells, M., & Bradshaw, T. (2023). Implementation of Human Systems Integration technical and management process for the lunar Gateway Program. *Acta Astronautica*, *207*, 200–205. https://doi.org/10.1016/j.actaastro.2023.03.018

Stilgoe, Owen & Macnaghten, 2013
Stilgoe, J., Owen, R., & Macnaghten, P. (2013). Developing a framework for responsible innovation. *Research Policy*, *42*(9), 1568–1580.

Succini, 2023
Succini, L. (2023). Design per l'Innovazione Responsabile. In E. Formia, V. Gianfrate, & L. Succini (Eds.), *Design per l'Innovazione Responsabile. Guida per processi formativi in trasformazione*. Franco Angeli. https://series.francoangeli.it/index.php/oa/catalog/book/993

Succini et al., 2024a
Succini, L., Sindoni, E., Grizzaffi, L., & Pasini, V. (2024). Sustainable Life Beyond Earth. A Design Driven Living Lab to Create New Human Experiences in the Space Habitat. *IAF Human Spaceflight Symposium*, 834–842. https://doi.org/10.52202/078364-0095

Succini et al., 2024b
Succini, L., Celaschi, F., Ciravegna, E., Pasini, V. (2024). Responsible Advanced

Design. Achieving Sustainability through Collaborative Processes. *Theme de Disseny*, *40*. https://doi.org/10.52202/078364-0095

Succini et al., 2025
Succini, L., Ciravegna, E., Giardina, C. (2025). Fostering regenerative processes through advanced design and responsible innovation: The emergence of collaborative and ethical practices in complex sectors. the case of the packaging system. In C. Cobreros, E. Giorgi & T. Cattaneo (Eds.), *Regenerative Design New Contexts, New Visions, Emerging Practices and Perspectives*. Springer Nature. https://doi.org/10.1007/978-3-031-76890-3_4

Van Ellen et al., 2023
Van Ellen, L., Bridgens, B., Burford, N., Crown, M., & Heidrich, O. (2023). Adaptability of space habitats using the Rhythmic Buildings strategy. *Acta Astronautica*, *211*, 764–780. https://doi.org/10.1016/j.actaastro.2023.06.045

Yashar, 2023
Yashar, M. (2023). Life at the edge: Design concepts in remote & extreme earth-environments as testbeds for future lunar development. *ASCEND 2023*. ASCEND 2023. https://doi.org/10.2514/6.2023-4710

Zannoni et al., 2024
Zannoni, M., Succini, L., Rosato, L., & Pasini, V. (2024). Transitional industrial designer. La responsabilità di progettisti e imprese per una transizione sostenibile | Transitional industrial designer. The responsibility of designers and companies for a sustainable transition. *AGATHÓN 15*, 332–343. https://doi.org/10.19229/2464-9309/15282024

ADVANCED DESIGN STRATEGIES FOR SPACE HABITATS: BRIDGING HUMAN FACTORS AND DIGITAL TOOLS FOR ENHANCED LIVING ENVIRONMENTS

Veronica Pasini, Carolina Beccari**, Valentina Gianfrate*, Lucia Grizzaffi***, Raffaele Montemurro*, Lorenzo Rocci***, Andreas Sicklinger*, Elia Sindoni***, Laura Succini**

1. Introduction

In the field of space exploration, changes are occurring rapidly, in different spheres: from political/governmental to social, economic, and cultural ones (OECD, 2019). An increasing push toward the democratization of Space has been characterized by significant changes across various levels of analysis:

- Macro-scale: The integration of commercial actors is expanding, highlighting the growing importance of the private sector in space governance, infrastructure development, and the commercial use of orbital spaces;
- Meso-scale: The space economy is diversifying. The arrival of companies not traditionally associated with the space sector, contributing to technological developments, production, and new services, is creating novel entrepreneurial opportunities;
- Micro-scale: The design field is opening up to a broader range of designers, fostering greater cross-disciplinary and cross-competence contamination. Furthermore, the democratization of space is creating new opportunities for users, enabling wider participation in space infrastructure and services.

Within this framework, beyond the dimensions of geopolitics and security, urgent issues emerge that require intervention: the psycho-physical well-being and interpersonal relationships of future crews, both in short- and long-duration missions.

The study *Beyond the Space Life. Digital Living Lab for Human Life in Space* (Project 1.10 of the MICS extended partnership)—object of the previous chapter of this publication—explores how the evolution of the concept of well-being is crucial with-

**Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

***Department of Mathematics, Alma Mater Studiorum - University of Bologna, Italy*

****Thales Alenia Space Italia*

in microgravity environments (Kanas & Manzey, 2008) especially for a context where space exploration will be accessible to new users (NASA, 2020) and it constitutes the methodological foundation for this contribute. The ideation phase of the design process is assumed as an initial touchpoint, where the user's psychological, emotional, and perceptual characteristics become drivers (Vakoch, 2012) for a more adaptive, responsible and advanced design approach (Succini et al., 2024).

Thanks to the competences and knowledge of Thales Alenia Space Italia (TASI), the theoretical analyses and considerations initiated on the integration of additional factors capable of enhancing behaviors and psycho-physical well-being in the design of pressurized orbital interiors are further explored and tested within TASI's design processes. To achieve this, systemic-level improvements are introduces, to support the application of an advanced design methodology (Celaschi, 2016; Celaschi et al., 2019) to foster forms of knowledge and design more inclusive and attentive to the needs of an increasingly less-trained and non-specialist users' base.

With the aim of optimizing design times and processes from both digital and virtual perspectives, the research also focuses on analyzing the current pipeline to improve the simulation and visualization of the 3D model and its surrounding environment. This approach enables the reduction of development times for designers' practices, thereby positively affecting the environmental impact of the design process.

In addition to highlighting these aspects, the contribution emphasizes how interdisciplinarity, together with the role of design as a mediator of knowledge (Celaschi, 2008), can foster greater accessibility within this context. The acceleration of the process of collaborative knowledge can support future designers approaching this field in developing innovative concepts.

2. Current processes for the analysis of habitable areas in deep space environments

The analysis of Space environment and habitats is a multidisciplinary process that has always combined space engineering and ergonomics. This approach considers the extreme condi-

tions typical of the extraterrestrial environment, including microgravity, isolation, and the limitation of spatial and functional resources (Dominoni, 2021; Bannova, 2021). However, it predominantly focuses on addressing strictly engineering-related aspects, incorporating human factors (NASA, 2014) almost exclusively to meet the essential needs of astronauts.

Current methodologies throughout the design phases are supported by both digital tools and physical prototyping. The former rely on the use of advanced computational modeling tools, such as CFD (Computational Fluid Dynamics) simulations and FEM (Finite Element Method) analyses, aimed at optimizing functional and technical aspects including airflow distribution, structural integrity assessment, and material behavior prediction under microgravity conditions (Green et al., 2017; Singla & Shirke, 2024). All these analyses are fundamental for crew safety.

Similarly, physical prototyping plays a fundamental and indispensable role, especially in relation to the expected standards. The recourse to tests conducted in terrestrial environments could replicate space conditions, such as simulations carried out in extreme environments like Antarctica or underwater settings. Low-fidelity prototypes, on the other hand, are essential for validating interior configurations (Jelonek, 2024). Currently, this phase accompanies the design process at various stages, repeating based on the feedback received. However, this iterative process, necessary due to the sector's complexity, entails high costs and raises issues concerning the sustainability of the process.

Academic and industrial communities are exploring to optimize some of these processes is the integration of immersive technologies (Juan et al., 2022), such as Virtual Reality (VR) and Augmented Reality (AR), that offer the possibility to simulate the user experience also in remote spaces, enabling a more detailed and immersive evaluation of the proposed solutions (HERA and VECTION are two different experimentations in which AR and VR have been tested, demonstrating their potential).

To date, as highlighted during the 75th International Astronautical Congress (IAC) held in Milan in October 2024, the predominant use of virtual reality offers clients a broader audience the opportunity to experience an orbital habitat or to showcase

the final layouts of a project. However, international research centers and companies are seeking to integrate these technologies into various stages of the design process to address emerging challenges in terms of economic efficiency, environmental sustainability, and the democratization of space (Basu et al., 2021; Holt, 2023). This integration facilitates the analysis and experimentation of new design configurations (Wang, 2009) and human engaging (Lee et al., 2023), but however they cannot replace final prototyping and the related verification phase, which will remain necessary to meet NASA standards (NASA, 2017).

The ongoing study, building upon the analyses conducted, focuses on the integration of digital technologies in the initial conceptual phase of the design process, aiming to consider and monitor individual well-being from the earliest stages of concept development.

As previously mentioned, the design of living spaces in space environments requires particular attention to ergonomic and human factors. While ergonomics provides the technical foundations for designing functional and adaptive spaces, the study of human factors introduces a deeper dimension, oriented toward the well-being and psychological sustainability of individuals.

3. How ergonomics and human factors affect design for well-being in microgravity environments. Hints and implications

The voluntary and involuntary condition of humans in Space relate to modified interaction with surroundings as well with physiological changes, that can only partly be contrasted by determined actions. Hence, human factors in the specific context become clearly of crucial importance, as the human dimension relate to (free floating) movement in search of stable positioning, motion through space by using holders, as well as the interaction with all panel commands and cognitive matters such as noise, light and smell relate to immediate safety issues. Any impertinent use or interpretation of space station or orbit vehicle parts can lead to devastating catastrophe up to instant dead of passengers on the station in orbit. Human factors on the other hand are well studied, the discipline counts on innumerable experimentation and tests of any kind of activity that

needs to be monitored and consequently improved. More than anywhere else than in space, this is the case and must be. Nether the less, the environmental conditions are radically different from conditions on earth with regular gravity, that balances any action (movement, pressure, force, etc.) to the muscle force humans have and exercise in any regular and irregular circumstances: "The focus of ergonomic design is on the human being with his or her individual performance requirements such as height, physical strength, abilities but also eyesight, reading and writing ability and specialist knowledge." (Schmauder & Spanner-Ulmer, 2014, p. 19). From this generic description, the further indication for a correct ergonomic environment relay on "consideration of the environmental context, i.e. the physical, organizational, social and legal environments must be identified and described." (Schmauder & Spanner-Ulmer, 2014, p. 19).

In consideration of this, the NASA documentation Human Integration Design Handbook, in its 2022 updated version related to anthropometry, confirms that the design references need to include Anthropometry, the Body Surface Area, Body Volume and Body Mass, as well dimensions regarding interaction such as Range of Motion and Reach Envelope. The same documentation discusses the already ongoing development of major variabilities related to human dimensions.

"Although NASA maintains databases of current (active) astronaut anthropometry, this data is not necessarily the best estimate for future astronauts. While it may be useful for current and ongoing human factors analyses and investigations, it may not fully represent the variation among the population from whom the astronauts are selected." (Childress & Coffey, 2022, p. 5).

Considering the current evolution of Space Economy, with the already ongoing dispatch of space travelers who are not trained astronauts, this last sentence reveals particular importance. Based on the changes "sources such as modified military and civilian databases may be more appropriate representations of a future astronaut population." (Childress & Coffey, 2022, p. 5).

The current geopolitical condition seems to newly separate space missions between geographical areas with related anthropometrical differences. Thus, it could seem suitable to keep on the idea of commonly and globally shared spaces in orbit which

today however includes besides American statistics only European references. But in a long-term project programming, this might be very limiting. The recent ISO/EN 7250-2 (update in progress) might give a better overview of national populations, as it lists anthropometrical data from different countries. The problem keeps alive when it comes to designing for multiple population references. The proposed design strategy includes to use same product in different sizes (especially when it comes to clothing, this characteristic appears evident), of an adjustable product, that can be sized to personal comfort. At the same time, as Juergens, Matzdorff and Windberg (1998) are underlining, there are critical dimensions, that cannot be changed: "The "critical measurement" needs to be determined, for instance concerning doors and other passageways, the critical measurement will be based on the highest percentiles of body height in a given population. [...] in determining the critical measure, the "average person" can again play a role." (Jürgens, Matzdorff & Windberg, 1998, S. 3-4).

Following the reasoning of the authors, who discuss in the paper the possibility to generate an artificial "European Man" by using lowest and highest measurements as border data, the result might be staying in the middle: "A compromise concerning a differentiated solution was found in defining the median (P50) of all measures of the European population by way of the all-European calculation, while the limiting percentiles P5 and P95 were to be set according to the countries hosting the highest and lowest body measures in their population respectively. [...] In order to avoid a too extreme "straddling" of the limiting percentiles, it was agreed that the "extreme" countries would fix the upper and the lower percentiles respectively, but that they would not be differentiated according to sex, but rather average between women's and men's values." (Jürgens, Matzdorff & Windberg, 1998, S. 3-4).

This last proposal could overcome another concern of NASA, as the data of female astronauts is even lower that the already low data available for astronauts in general. At the same time, it could be examined if the difference between NASA standard using P99 and P1 instead of P95 and P5 covering sufficiently in this way the differences of population of different geographical areas. As defined by the same document, two design aspects

are mainly to be addressed by anthropometrical dimensions as critical measurements: clearance (door-pathways) and Reach or Access.

In addition to this, significant anthropometrical variations can be observed (in addition to the "traditional" ones) in the clothing. Not necessarily limited to the specific role of an astronaut (f.e. team leader of generic space traveler), any crew member faces temporarily the need of wearing pressurized suits, either in docking activities while arrival and departure, but also in any emergency or programmed spacewalk. Further, it is important to add as an anthropometrical adaptation in space, that the assumed posture of the human body in a zero-gravity environment changes drastically the overall body imprint in space: the body assumes a sort of embryonal form, leading to less height but increased depth, with more limitations in frontal reach. From this should be assumed further that ability in dealing with the own body in the unusual condition of zero-gravity need learning and experiencing once arrived in orbit, a period during which the physical data of human dimensions need to be evaluated differently as unprecise movement and interaction exceeds the regular range of body imprint in space. This in particular, as different kind of space travelers with less preparation exercise on ground might be unprecise in movement, and even find enjoyment in experimenting unusual body movements.

4. The concept of well-being in the design of space habitats

The analysis presented highlights the need to redefine the relationships between: humans and the environment, humans and each other, and humans and their inner selves.

One of the initial phases of the research therefore focused both on an in-depth analysis of the state of the art—examining operational platforms in orbit, such as the International Space Station (ISS) (*first module launched in 1998, with decommissioning planned around 2030*) and Tiangong (*first module launched in 2021, with planned expansion in the coming years*)—and on mapping emerging concepts proposed by private companies.

Despite significant advancements in the design of space habitats having improved comfort through the introduction of

human factor-oriented principles, such interventions remain rooted in a system originally designed to prioritize technical efficiency over user experience. However, with the expansion of the user base and the introduction of new perspectives—such as space tourism and the privatization of space access, as previously mentioned—it becomes essential to rethink design paradigms to meet broader and more diverse needs.

Regarding the state-of-the-art investigation, the ISS represents a fundamental case study due to its long operational history, which provides valuable lessons in iterative design. The station's modular structure has allowed for continuous adaptations over the years, integrating astronaut feedback to optimize usability, safety, and comfort. The evolution of functional zones—such as those dedicated to rest, nutrition, and personal care—has highlighted the importance of ergonomic design increasingly oriented toward psychological well-being, particularly in confined environments (NASA, 2023).

Similarly, the Tiangong station, with its more recent modular design, incorporates improvements in flow management and reduces interference between operational and recreational areas (CNSA, 2024).

In parallel, the mapping of emerging concepts (tab. 1)—such as *Airbus's LOOP project, Gravitics's Starmax, and Sierra Space's Orbital Reef*—has revealed significant innovations aimed at improving the human-environment interface. These design concepts place particular emphasis on elements such as biophilic integration and visual access to the external environment, supporting not only physical orientation but also psychological stability and the emotional connection between interior and exterior spaces (Galan Madruga, 2010).

The interaction between humans is also considered, particularly to promote teamwork and social cohesion. Some of the analyzed concepts focus on creating more shared spaces to encourage collaborative activities. This aligns with psychological studies conducted in extreme environments, which highlight the necessity of fostering interpersonal relationships to mitigate the effects of isolation and stress during long-duration missions (Kanas & Manzey, 2008).

Finally, the relationship between the individual and their inner self is addressed through customizable lighting elements,

adaptable layouts, and soundproofed modules to meet the diverse needs of users, ensuring a certain degree of autonomy within a shared habitat. These aspects reflect a broader trend toward personalized environments aimed at enhancing the living experience in space.

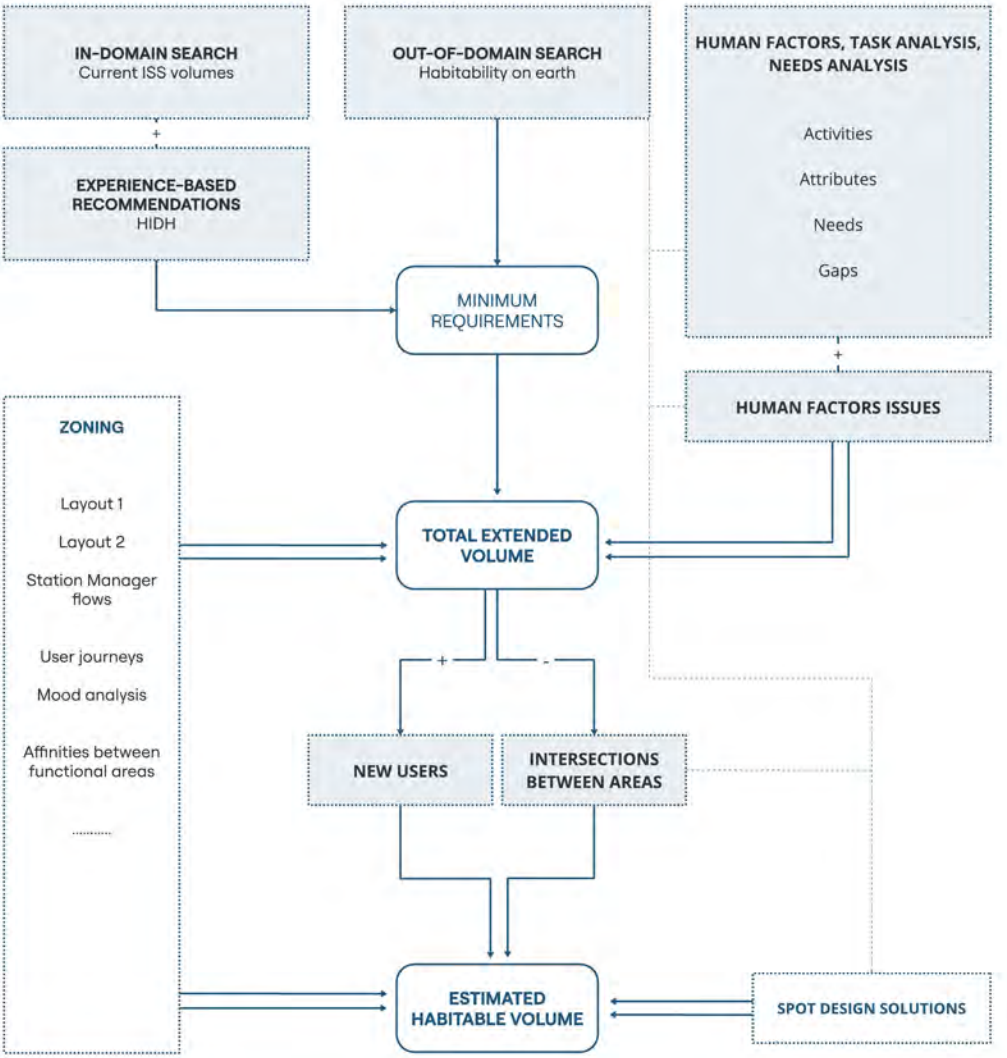
This section of the research highlights the increasingly central role of specific factors related to individual and community well-being in the design of space habitats. As will be further explored, this information will contribute to defining the future needs of new astronauts while consolidating the fundamental ones.

Tab. 1. Summary Table of the Preliminary Analysis of the Case Studies, showing in which factors aspects the different projects are driving the habitation design, based on a visual research and on the description on the reference websites, as they are purely concept. Adapted and improved table from Zakonyan et al., 2024.

Reference project	Axiom Station	Loop	Orbital Reef	Starmax	Voyager Station	Vast Station
Main partners	Axiom	Airbus	Sierra Space Blue Origin	Gravitics	Gateway Foundation	Vast
Concept	x	x	x	x	x	x
Light System	x					x
Biophilic System		x	x			
Storage System	x	x	x	x		x
Flow optimization		x				
Sound optimization			x	x		
Openings to the outside	x		x	x	x	x
Working life and daily life division			x			
Social spaces			x		x	x
Personal spaces		x				x

5. Advanced design tools for interdimensional analysis: Bridging state-of-the-art research and emerging needs

With the aim of incorporating these reflections into the project, a multi-level research framework has been developed. When integrated, these levels have led to the definition of configurations and design constraints that consider the evolution of uses, needs, and practices occurring in other domains (fig. 1).



1. Methodology used in defining the volumes of functional areas for a habitation module interior concept of a future commercial station. All images are reproduced in color in the online edition of the book.

To propose guiding factors and characteristics for design, it was necessary to start from the principles currently adopted in the design of space habitats. It was essential to examine how these relationships intertwine in other terrestrial environments (not included in NASA standards), compare them with the emerging needs identified through case study analyses (as previously described), and consider the new user archetypes.

This working framework was structured into three phases: in-domain research, out-of-domain research, and user needs analysis.

5.1. In-domain research

The experience accumulated over decades of space activities and life in space represents an invaluable resource for guiding future designers. Documents such as the *Human Integration Design Handbook* (HIDH) (NASA, 2010) and the *lessons learned* (Baggerman et al., 2004) collected from previous missions provide a consolidated methodological framework, the result of iterative design processes and retrospective analyses. These tools allow for the early consideration of livability issues during the design process, which, despite being extensively documented in the literature, have not yet been translated into mandatory requirements.

Another significant contribution to the design of space habitats comes from the analysis of analogous terrestrial environments that share comparable conditions with space. In this regard, the *NASA STD-3001* document (NASA, 2023) provides an analysis of habitable volumes and their relationship with the number of crew members, using references derived from terrestrial and maritime living spaces (e.g., vessels).

These data, along with current regulations and guidelines, form a starting point for identifying key parameters in defining future space habitats. Given the anticipated expansion of the user base and the introduction of new perspectives, these parameters will need to be integrated to meet broader and more diverse needs.

5.2. Out-of-domain research

The design of future space habitats requires the adoption of advanced analysis tools based on design-driven approaches that

incorporate innovations from the earliest stages of the design process. It is therefore necessary to broaden traditional references by including living models from different experiences than those already considered in the reference literature. This approach is essential since the motivations and expectations of future "astronauts" will differ from those of traditional ones. After a thorough investigation, minimal habitats in which user experience and relationships play an important role were selected and analyzed, such as capsule hotels, RVs and boats. Such contexts offer insights to identify configurations of minimal habitable spaces and to develop strategies to resolve conflicts between various activities and functions within compact environments. Furthermore, in these confined environments, the multi-functionality of spaces becomes a prerequisite for optimizing the use of available resources and preventing the prolonged non-use of areas dedicated to specific functions. The analysis of the user experience conducted on terrestrial and currently in orbit (ISS and Tiangong) environments led to the identification of main macro-activities.

The activities identified—rest, personal care, meal preparation and consumption, training—were then used in the further research and in the comparison of the minimal living models.

The analysis of the volumes of space dedicated to these activities in the selected terrestrial environments (capsule hotels, campers and boats) was supplemented with a study of the spatial relationships and affinities between the different functions.

The analysis presented (tab. 2) outlines a summary of the state of the art regarding the dimensions of the cockpits under study and a comparison with the ISS. In particular, the main typological categories were identified, analyzing the most widespread models on the market. For each typology, an analysis of minimum and average dimensions made it possible to determine optimal conditions for habitability. This process considered the specific activities carried out inside the passenger compartments and defined the correlation between volumes and functions.

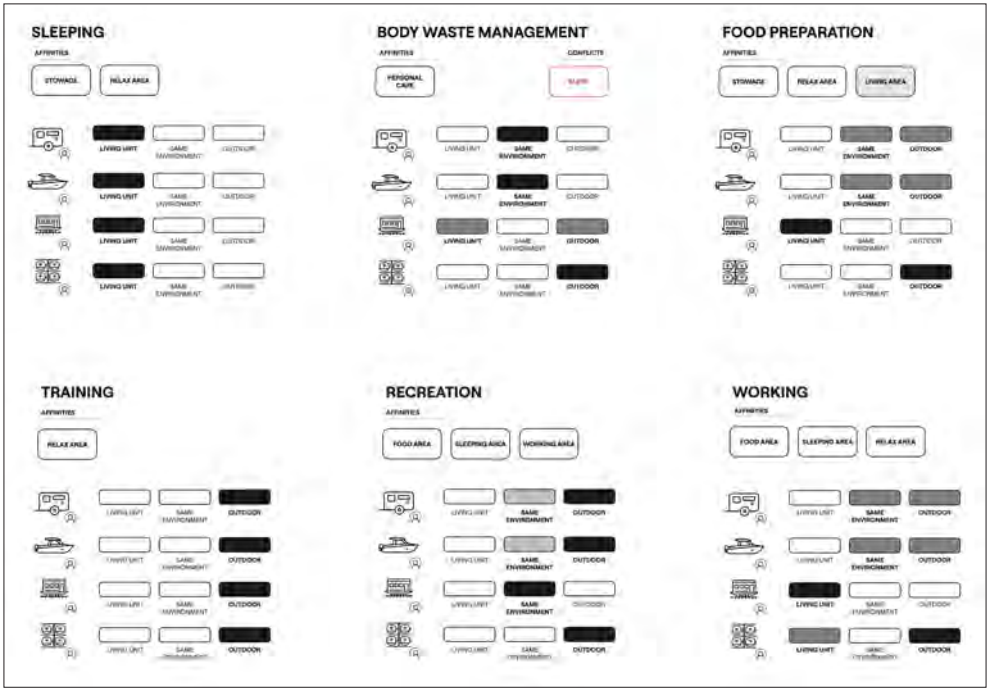
Tab. 2. Results of out-of-domain research across various research fields, categorized by functional areas and in relation to the estimated current volumes on the ISS.

Functional Area	Boats	Capsule Hotel	Recreation Vehicles	Train Berths	ISS
Rest	3,2 m2	2,4 m2	3,2 m2	2,6 m2	3.32 m3 **1.50 m3** for sleeping. **0.63 m3** for stowage of operational and personal equipment. **1.19 m3** for donning and doffing clothing.
Personal care	3,0 m2	External Area	2,2 m2	2,4 m2	Approx. 3.9 m3 including facilities
Food Processing and Food Consumption	3,8 m2	External Area	2,2 m2	0,4 m2	16 m3
Physical Activity	/	External Area	External Area	/	24 m3
Leisure	/	External Area	External Area	0,4 m2	Approx. 70% of 388 m3

In parallel, the qualitative analysis of the selected terrestrial layouts made it possible to identify recurring structural elements. Particular attention was paid to the study of the configuration of the functional unit destined for rest and sleep, similar to the current *crew quarters* of the Space Stations (fig. 2). The in-depth study of the spatial relationships between this unit and the other functional areas provided useful indications for improving livability and fostering the harmonious integration of functions within the habitats planned for the future.

The analysis of these different layouts and space hybridization solutions offered insights into the possible configurations of future commercial space stations and the design of environments according to a task-driven approach. Among the results that emerged, one element of particular interest stands out: the outdoor space, which has not only functional, but also social and psychophysical relevance within these minimal units.

Although in the context of spatial design, direct contact with the outdoors represents an intrinsic and insurmountable



2. Representation showing the position of functional areas in relation to the living cell where users sleep. The aim is to evaluate their connection to the sleeping area, measure the level of intimacy required for each activity, and assess their integration with other activities. It also highlights usually associated activities and potential conflicts with other functional zones.



3. Functional areas analyzed during this research, with related actions to be carried out in these spaces. During the design phase, they are overlaid on the basis of functional and experiential compatibilities and affinities.

limitation, it is evident how, through careful design of interior spaces, actions or moods can be brought back to recreate the beneficial effects typically associated with it.

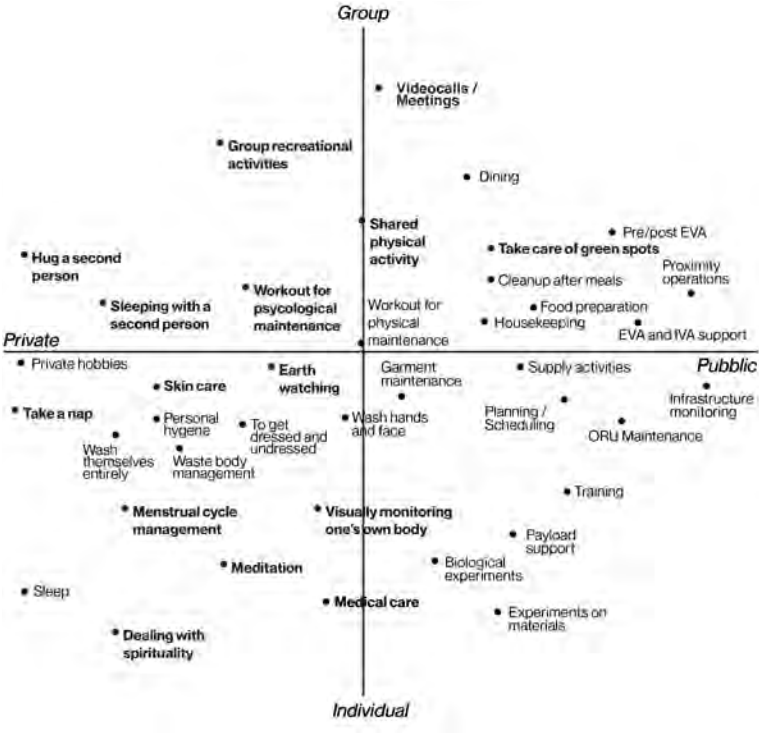
5.3. User needs analysis

The work carried out, together with the research on future users (described in the previous section) and the analysis of human experiences and relationships in confined environments, has been crucial for defining the functional areas, related actions, and associated needs.

In establishing these elements, it was essential to integrate constraints and regulations defined by NASA. In particular, the *Human Integration Design Handbook* (HIDH) (NASA, 2010) provides detailed guidelines on the various environments within the station and the activities that, based on past experiences, could compromise the proper functioning of the habitat. This document serves as a reference to ensure that the spatial organization supports the crew's operational, physiological, and psychological needs while adhering to established safety and usability standards.

The clustering described in figure 3 introduces, on the one hand, new spaces dedicated to personal well-being and care, and on the other, allows for identifying and addressing critical issues or opportunities related to existing activities, such as those observed on the ISS. The actions within each functional area are closely linked to the explicit and implicit needs of future user archetypes. These were validated and integrated through specific tools, including questionnaires, workshops, and ongoing discussions with the TASI team.

For this component of the research, the distinction between individual and group activities, as well as between public and private spaces, plays a key role in developing guiding strategies for new configurations that are more focused on human and community well-being in space. Building upon those described by NASA (NASA, 2023), the activities have been enhanced to foster a more collaborative and experiential relationship between environment-human, human-human, and human-self (fig. 4).



4. The image presents a reworked version of the framework proposed by NASA in 1995 (ref. 319, p. 60 of NASA Standard 3000-86). The model has been adapted and integrated with additional activities (in bold) and variable environmental attributes, enhancing the original classification. In this new iteration, operational requirements are combined with human-centered considerations, focusing on optimizing the interaction between astronauts and space environments. The implementation of these modifications provides a more comprehensive and dynamic view of space-related needs, aiming to create habitats that are both functional and adaptable, addressing both technical aspects and human requirements.

5.4. Application of advanced design tools: initial configurations

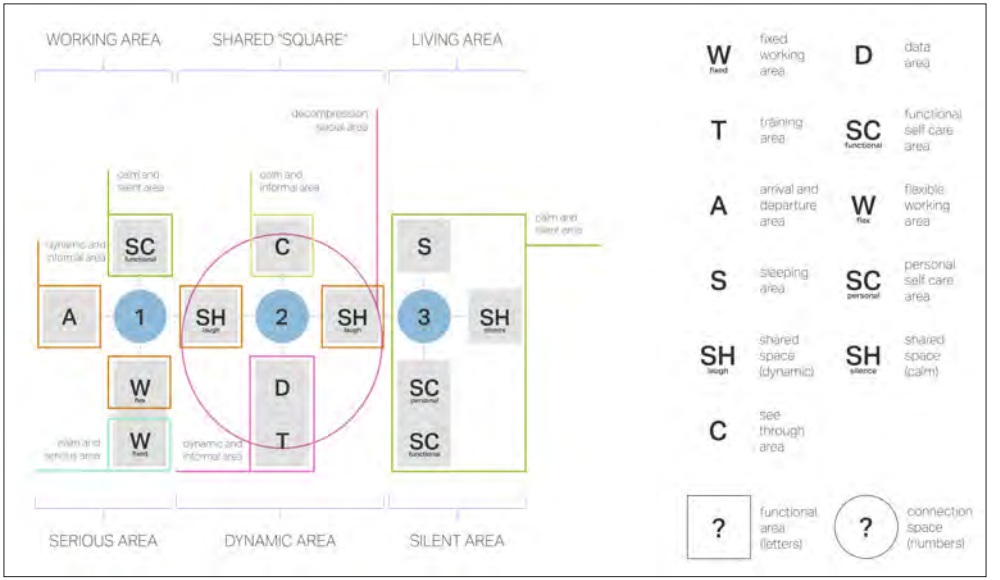
The presented research process was tested by hypothesizing a future commercial orbital station. This led to the development of a potential configuration that considers the guiding principles derived from both domain-specific and cross-domain research, as discussed in the previous sections. This initial outcome proposes a new distribution of functional areas. At this stage, the identified areas are not specifically linked to space modules nor, more generally, to volume allocation; instead, they are developed following two dimensions, consistent with the current configuration of the international segment of the ISS, in order to avoid constraints arising from specific technical requirements (such as those related to docking).

The configuration (fig. 5) features three distinct environments, respectively dedicated to work-related, communal, and individual activities. At the center of the layout lies a multifunctional area intended for leisure time, meal preparation, and consumption, serving as a "central square." This space was conceived based on research insights and aims to foster social cohesion and community processes, enabling continuous transformation of the living environment according to immediate needs. Connected to it are areas designed for well-being and stress mitigation, including spaces for physical training, biophilic zones, and a "see-through" environment (fig. 3)—an area that allows observation of the external extreme environment, intended to address the psychological effects of orbital conditions, particularly those related to isolation.

In the proposed configuration, particular emphasis has been placed on the arrival and departure phases of the astronauts. It is hypothesized that the arrival spaces can contribute to enhancing the experience and facilitating adaptation to life in space, while, during departure, they can support the "detachment" operations.

This initial application of the design method, also discussed with industry experts, made it possible to verify the effectiveness of the analysis and design process while simultaneously highlighting crucial areas for the subsequent design phases:

1. Recreational Activities and Free Time: The need to prioritize recreational activities and, more broadly, the crew's



5. Conceptual layout figured out matching the research (in and out of domain) of the State of the Art and the human factors involved. The key aspect to highlight in this representation is the concept of "shared square," a common unconventional living space (image already shown as an example in Zakonyan et al. 2024).

free time has been underscored. This involves designing public spaces not dedicated to laboratory use, characterized by flexibility, partitionability, and architectural elements capable of simulating or evoking open environments to foster social cohesion.

2. Spaces Defined by Emotional and Experiential Parameters: A critical insight is the importance of defining spaces based on parameters tied to desired emotional impact, activity affinities, and user experience types. It becomes essential to design spaces that can be perceived as, for example, calm or energetic, formal or informal, depending on functional and psychological needs.
3. Rethinking Training and Microgravity Countermeasure Areas: The research suggests a paradigm shift in the conception of training areas and those dedicated to counteracting the effects of microgravity. Considering the significant time spent on these activities, there is an opportunity to rethink them to integrate recreational and social dimensions. This hybridization could significantly enhance onboard quality of life, transforming physical exercises into experiences that also promote psychological well-being and social interaction.

The results obtained provide the foundation for a holistic and flexible approach to the design of future space habitats, focusing on well-being, community dynamics, and the optimal integration of functional and emotional needs (Häuplik-Meusburger & Bishop, 2021). This research phase supports the definition of the design process and the digital tools intended for future designers, contributing to the improvement of specific design actions both in terms of material sustainability (e.g., execution times) and immaterial aspects (e.g., project accessibility).

6. Thales Alenia Space case study

As anticipated in the introduction, Thales Alenia Space Italia, in addition to being a project partner, serves as the application case in which to explore and experiment with the emerging design strategies, analyzing their strengths and weaknesses.

Given the wide range of professional figures involved in the design process of a pressurized habitat, it was necessary to structure the investigation process and the experiments along multiple strands, each providing partial results that, when interconnected, contribute to achieving the main goal of the research: the *Space Digital Living Lab* (Zakoyan et al., 2024; Succini, 2024).

This tool, designed to assist designers, serves as a space for knowledge sharing and early conceptualization of habitats for extreme environments. Among its key components is a demonstrator that, in its initial conceptual phase, supports the study of a dynamic configuration of the space habitat. This approach ensures greater attention to the personalization and flexibility of spaces, as well as to the psychophysical well-being of future space travelers participating in new missions.

To conceptualize an initial prototype of the demonstrator, it was necessary not only to design its architecture, user experience, and content interactions but also to correlate the preliminary research findings—focused on emerging needs and actions—with Thales Alenia Space Italia's (TASI) design systems. Additionally, efforts were made to enhance the data transfer pipeline between CAD models and virtual environments.

To this end, the following two chapters describe the actions undertaken to make the current design process more practical and sustainable at a systemic level, while improving the speed and efficiency of data exchange:

- Interactions between existing tools and new design inputs through the integration of emerging needs and functions of future users into Thales Alenia Space Italia's (TASI) Model-Based Systems Engineering (MBSE) framework;
- Optimization of modeling processes to enhance the design and utilization of virtual environments characterized by microgravity conditions.

6.1. MBSE: bridging human-centered insights and engineering in space habitat design

Currently, for the design of space habitats, Thales Alenia Space Italia (TASI) adopts a systemic approach through Model-Based Systems Engineering (MBSE), a tool that organizes the design

process by connecting needs, actions, and functions, ultimately defining the functional architecture and its relationship with end users.

MBSE represents a convergence between exploratory design thinking and the systematic rigor of engineering. To effectively integrate new functions and needs related to the profiles of emerging users and their well-being, MBSE plays a fundamental role in transforming complex requirements into actionable solutions. It provides tools to map needs into logical structures, operational functions, and physical components, ensuring that every aspect of the module meets the diverse requirements of the users.

In this context, the definition of new user archetypes and their needs has been implemented within the MBSE framework, creating a structured approach that gradually guides the progressive system definition. Specifically, for less experienced travelers, additional requirements related to comfort, entertainment, and safety have been considered to ensure an adequate experience in space environments.

The starting point of the MBSE process is the operational analysis, which involved identifying activities, needs, and their implementation in *Capella*, an open-source MBSE tool. The clear definition of requirements enabled the identification of the primary objective for the new modules: ensuring a fully operational habitat while optimizing comfort and the management of new users.

Following the operational analysis, a high-level system analysis was conducted to identify the common functions between a crewed space module and a commercial one. Although the specific subsystems have yet to be defined, the analysis has begun to outline the key properties required by the module. For instance, while both types of modules must support communication functions, the new module necessitates a system that goes beyond operational and emergency communication, incorporating solutions tailored to more personalized and frequent personal communication. This highlighted the need for more intuitive and flexible systems to enable new users to stay connected with their loved ones on Earth or collect memories to view during their stay on the station.

The final phase of the MBSE implemented at this stage of

the project focused on defining the operational architecture, emphasizing how the system functions to meet stakeholder expectations. In this phase, the subsystems were defined as logical components, to which more detailed functions—referred to as "logical functions"—were assigned. As a higher level of abstraction than physical components, logical components can later be further decomposed into specific hardware and software in subsequent stages. To meet the requirements of this project, two distinct logical architecture schemes were developed:

- The first provides an overview of the commercial module system, representing all the main logical components and their interactions;
- The second focuses on the logical components derived from an in-depth analysis and discussions with partners, paying particular attention to traveler needs and suggesting potential hardware solutions to meet those requirements.

Regarding the physical components derived from this process, several concepts were selected during collaborative design activities involving researchers, young designers, and the company TASI. These outputs were subsequently integrated into the MBSE, linking them to needs and actions, and later incorporated into the modeling database, where they were converted into virtual reality files. This approach enabled the development of a design flow that facilitates the selection of systems and products best suited to user needs while maintaining a continuous relationship between systemic design and the VR model.

In this context, further experimentations are planned, as the integration of virtual reality into the MBSE is believed to make certain observations more immediate, allowing for earlier assessments of the design process. Currently, these evaluations are conducted exclusively on physical prototypes and through the analysis of their interactions.

6.2. Optimizing the pipeline for improved design and utilization of virtual environments in microgravity

In recent years, virtual reality has been successfully integrated into aerospace industrial processes, particularly for construct-

ing virtual scenarios capable of replicating the environments and dynamics of aerospace activities. These scenarios of this chapter directly support the design process of space modules, allowing the verification of ergonomic requirements through tools such as virtual mannequins. Research has focused on a threefold objective: the improvement of the process of importing CAD models and creating new models, and the use of virtual mannequins, again starting with the heritage of TASI.

Synchronization with the CAD baseline. Components from CAD modeling, which generally derive from a previous design phase or are subject to changes during the project, must be simplified and converted into polygonal meshes for use within the *Unreal Engine* software, with which the virtual scenarios are created. For this purpose, the Datasmith features were used, perfectly integrated with *Unreal Engine*, which is able to manage a large variety of file formats typical of the CAD description. The imported meshes were simplified using the Nanite application, which allows for optimized rendering and storage based on the distance from the point of view. An *Unreal Engine* plugin was created that automatically processes all the components imported with Datasmith (typically tens, if not hundreds of thousands of elements) and their materials. The created features are easily usable thanks a specific graphical interface designed to be used within the *Unreal Engine* editor.

Interactive robotic arms. Typically, some elements imported into the scene need to be animated during the scenario simulation. Some simulations, such as the kinematics of single mesh components with simple shapes, are simple. However, if the animation concerns a more complex object, which is made up of multiple elements from the CAD design, such as a robotic arm, the creation of the control system for the animation of the object is more complex because it is necessary to transform the model into an articulated figure. Since in *Unreal Engine 5.0*, there is no system for creating a skeleton for an articulated figure, it was necessary to use external software, Blender, in this case. In this way, an animation system for robotic arms was created, capable of respecting all the movement constraints of

the model components, in particular controlling the robotic arm's movement with the skeleton's bones inside it.

Meta-human. The meta-human is a new type of virtual mannequin that can act as a user's avatar and can be controlled by tools such as a helmet and HTC Vive remote controls.

A new resource based on the Meta-Human integrated with *Unreal Engine* is being studied, which implements additional features specific to aerospace environments.

When the Meta-human is used as an avatar in virtual reality simulations, the user must be able to identify with the mannequin and move in the virtual scenario. To this aim, the created resource was inserted as the main component in a *Pawn*, a particular type of actor controllable by the user, that contains all the functions for interfacing with the input devices, including remote controls and a helmet. The mannequin's animation system was then modified to synchronize it with the movements of a possible user.

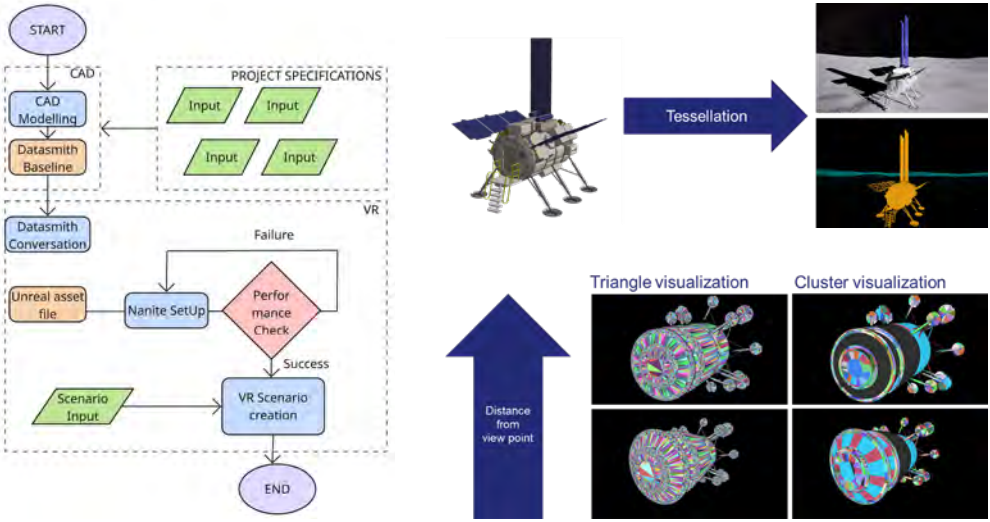
First results of TASE virtual design process

Synchronization with CAD baseline the new pipeline (fig. 6 and tab. 3) optimizes the synchronization with the CAD baseline and makes the generation of new VR scenarios starting from CAD models extremely fast.

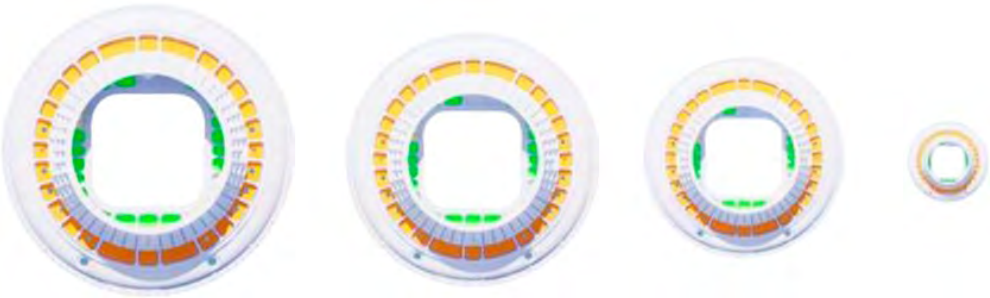
Tab. 3. Some results of the processing algorithm.

Memory Usage	Number of Meshes	Execution time
6.57 MB	8	13 ms
772.79 MB	137	1176 ms
8 202.64 MB	7 242	33 280 ms

More in detail, the activation of Nanite, especially on high resolution models, allows the navigation of the scenario at a constant frame rate that can reach up to 120 FPS (a minimum of 60 FPS is already sufficient to avoid problems related to motion sickness) in desktop systems, thanks to the dynamic mesh simplification system based on the distance from the point of view (fig. 7). Tables 4-5 report some results.



6. Flowchart: CAD to VR pipeline (left) and result example (right).



7. View with increasing distance.

Tab. 4. Mesh simplification tests carried out on a structural component of a pressurized module, varying the tolerance with respect to the chord.

Chord Tolerance	Triangles	Memory Usage
0.001 cm	11 668 170	617 313.562 KB
0.01 cm	2 025 294	109 616.781 KB
0.1 cm	706 430	31 035.848 KB
1 cm	579 864	22 937.609 KB
10 cm	575 112	22 529.648 KB

Tab. 5. Data from the rendering phase of the model analyzed in table 9.2 and fig 9.3, tiled with 0.1 cm tolerance with respect to the chord.

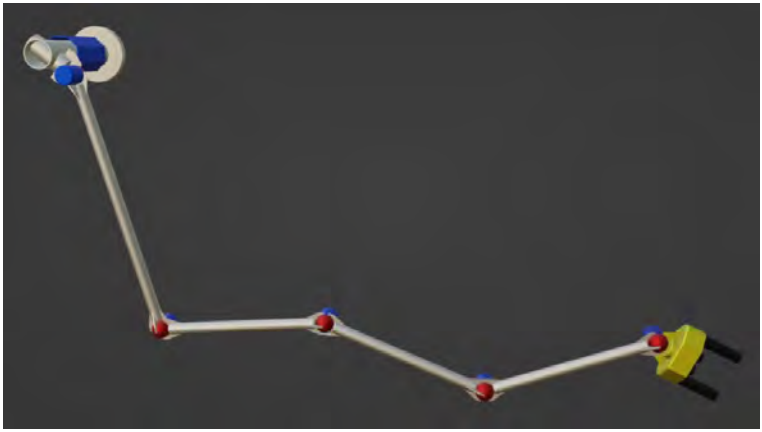
Model-camera distance	Triangles	Vertices	Clusters
10 m	139 383	207 175	1 108
15 m	100 567	157 943	804
20 m	70 033	114 348	571
50 m	20 716	37 064	211

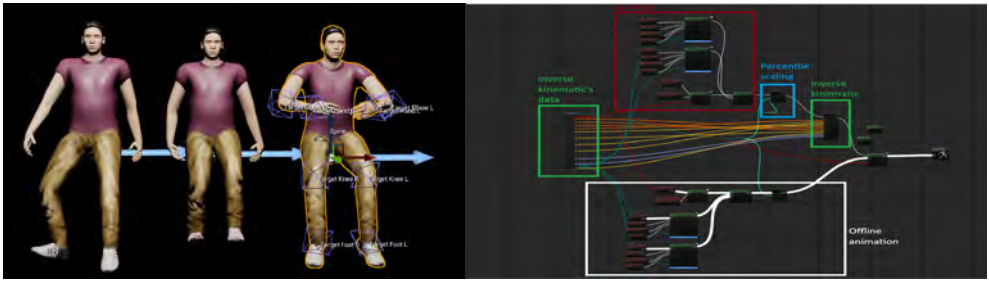
Robotic Arm Animation fig. 8 shows some poses of a model used within the virtual scenarios, which represents the robotic system present in the International Space Station. On the obtained Skeletal Mesh, a motion control system based on inverse kinematics is implemented using the IK Rig editor and the Full-Body-IK solver, which uses the pseudo-inverse damped least squares algorithm to obtain the rotations of the intermediate joints. This solver has proven to be the most efficient among those present in *Unreal Engine*, as the result given by its use faithfully reflects the actual physical movement of the arm, and it is the only solver that allows compliance with any rotation constraints of the joints.

Avatar Meta-Human The new Meta-Human resource (figs. 9 and 10) integrates additional features specific to aerospace environments:

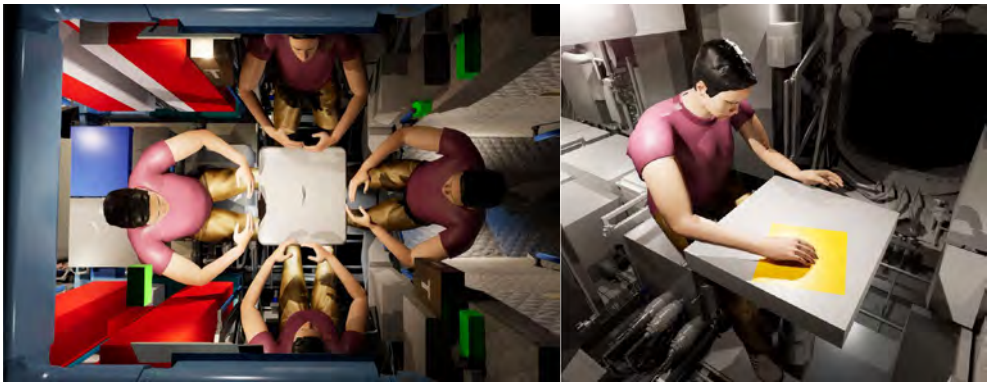
- An animation system based on inverse kinematics, that efficiently poses the mannequin within the scenario.
- Choice of the mannequin's gender;
- Use of the suit for extravehicular operations;

8. Robotic system poses.





9. Meta Human Rigged and relative Blueprints.



10. Result example whit Meta Human.

- The human percentile is selected based on gender and the chosen percentage, with consequent automatic and dynamic resizing;
- Possibility of being inserted into a virtual reality scenario to be piloted by the user.

The movement of the chain of bones of the articulated figure is divided into various sub-movements controlled through roto-translations of specific parts of the body according to direct and inverse kinematics techniques. In addition, what the mannequin sees in the virtual scenario is returned by a virtual camera in the Pawn and is used to reconstruct the video output in the helmet.

7. Conclusions

The integration of factors related to the future "astronaut's" well-being, their relationship with the environment and the crew, and the design of a new space experience represent a crucial challenge in developing sustainable and inclusive digital tools. These tools aim to support designers in creating microgravity habitats that are flexible and adaptable to various scenarios.

Within this framework, design plays a fundamental role as a mediator between technology, human needs, and operational contexts. By integrating interdisciplinary data, advanced technologies, and human-centered design approaches, it is possible to rethink the conception of space habitats, offering innovative solutions that open new perspectives for space exploration and habitability. Design transcends the mere resolution of functional problems, redefining the relationships between human and environment, human and human, and human and self.

This user-centered approach ensures that space habitats are designed to be comfortable and responsive to the continuously evolving needs of their inhabitants.

As highlighted, to make this design process increasingly adaptive and aligned with a more intangible vision of sustainability—placing the traveler's psychophysical well-being at its core—digital tools, supported by field research activities, play a

crucial role in integrating human factors in all their dimensions during the early stages of ideation and concept creation. These tools provide designers with real-time feedback on the impact of their design choices, both on the environment and on crew well-being.

Future research developments include the complete definition of the *Space Digital Living Lab* and its components, the prototyping phase of key elements, and enhanced interconnection between the various tools and systems that comprise it.

Authors contribution

This paper is the result of joint work of all the authors. Nevertheless, the authorship of "1. Introduction" is to be attributed to L. Succini; "2. Current processes for the analysis of habitable areas in deep space environments" to V. Pasini; "3. How ergonomics and human factors affect design for personal and community well-being in microgravity environments. Hints and implications" A. Sicklinger; "4. The concept of well-being in the design of space habitats" to V. Pasini and R. Montemurro; "5. Advanced design tools for interdimensional analysis: bridging state-of-the-art research and emerging needs" to V. Gianfrate, V. Pasini, R. Montemurro and L. Succini; "6. Thales Alenia Space case study" to C. Beccari, L. Grizzaffi, L. Rocci and E. Sindoni.

References

Baggerman et al., 2004
Baggerman, S. D., Rando, C. M., & Duvall, L. E. (2004). *Habitability and human factors: Lessons learned in long duration space flight*. National Aeronautics and Space Administration. https://www.nasa.gov/wp-content/uploads/2015/05/medical_habitability_and_human_factors.pdf

Bannova, 2021
Bannova, O. (2021). *Space architecture: Human habitats beyond planet earth*. DOM publishers.

Basu et al., 2021
Basu, T., Bannova, O., Camba, J. D. (2021). Mixed reality architecture in space habitats. *Acta Astronaut*, *178*, 548–555. https://doi.org/10.1016/j.actaastro.2020.09.036

Celaschi, 2008
Celaschi, F. (2008). Design come mediatore tra bisogni. In C. Germak (Ed.), *Uomo al centro del progetto: design per un nuovo Umanesimo* (pp. 40–52). Allemandi.

Celaschi, 2016
Celaschi, F. (2016). *Non industrial design: contributi al discorso progettuale*. Sossella.

Celaschi et al., 2008
Celaschi, F., Formia, E., Iñiguez Flores, R., & León Morán, R. (2019). Design processes and anticipation. In R. Poli (Ed.), *Handbook of anticipation: Theoretical and applied aspects of the use of future in decision making* (pp. 773–793). Springer. https://doi.org/10.1007/978-3-319-91554-8_48

Childress & Coffey, 2022
Childress, S. D., & Coffey, K. M. (Eds.) (2022). OCHMO-HB-004 Anthropometry, biomechanics, and strength. In *Human Integration Design Handbook (HIDH). National Aeronautics and Space Administration (NASA)*.

Dominoni, 2021
Dominoni, A. (2021). *Design of supporting systems for life in outer space: A design perspective on space missions near earth and beyond*. Springer International Publishing. https://doi.org/10.1007/978-3-030-60942-9

Galán Madruga, 2010
Galán Madruga, D. (2010). Psicología ambiental. Importancia de la educación ambiental. *Observatorio Medioambiental*, *12*, 241–246. https://revistas.ucm.es/index.php/OBMD/article/view/OBMD0909110241A

Green et al., 2017
Green, R. N., Ouellette, E. J., & Wey, C. C. (2017). *Progress towards a microgravity CFD validation study using the ISS* (NASA Technical Memorandum No. NASA/TM-2017-219651). NASA. https://ntrs.nasa.gov/api/citations/20170006556/downloads/20170006556.pdf

Häuplik-Meusburger & Bishop, 2021
Häuplik-Meusburger, S., & Bishop, S. (2021). *Habitats for our future extraterrestrial homes – Lessons from terrestrial analogues and our first habitats in space*. 50th International Conference on Environmental Systems. https://hdl.handle.net/2346/87046

Holt, 2023
Holt, S. (2023). *Virtual reality, augmented reality and mixed reality: For astronaut mental health; and space tourism, education and outreach*. Acta Astronaut. https://doi.org/10.1016/j.actaastro.2022.12.016

Jelonek, 2024
Jelonek, M. (2024). *Designing virtual reality laboratories for the evaluation of hazard perception and human behavior* [Doctoral Dissertation Universitat Duisburg-Essen]. https://duepublico2.uni-due.de/servlets/MCRFileNodeServlet/duepublico_derivate_00081617/Diss_Jelonek.pdf

Juan et al., 2022
Juan, Y.-K., Chi, H.-Y., & Zhang, Y. (2022). How much can VR improve spatial experience? – A case study with a commercial building project. *International*

Journal of Real Estate Studies, *16*(2), 75–85. https://doi.org/10.11113/intrest.v16n2.200

Jürgens et al., 1998
Jürgens, H. W., Matzdorff, I. & Windberg, J. (1998). *International anthropometric data for work-place and machinary design*. Arbeitswissenschaftliche Erkenntnisse N. 108, Bundesanstalt für Arbeitsschutz und Arbeitsmedizin

Kanas & Manzey, 2008
Kanas, N., & Manzey, D. (2008). *Space psychology and psychiatry*. Springer Netherlands. https://doi.org/10.1007/978-1-4020-6770-9

Lee et al., 2023
Lee, J.-K., Lee, S., Kim, Y., Kim, S., & Hong, S.-W. (2023). Augmented virtual reality and 360 spatial visualization for supporting user-engaged design. *Journal of Computational Design and Engineering*, *10*(3), 1047–1059. https://doi.org/10.1093/jcde/qwad035

NASA, 1995
NASA. (1995). *Man-systems integration standards* (NASA-STD-3000, Vol. I). National Aeronautics and Space Administration. https://msis.jsc.nasa.gov

NASA, 2003
NASA. (2003). *Human factors engineering requirements for the International Space Station: Successes & challenges*. https://ntrs.nasa.gov/api/citations/20110002790/downloads/20110002790.pdf

NASA, 2010
NASA. (2010). *Human integration design handbook* (NASA/SP-2010-3407). https://www.nasa.gov/wp-content/uploads/2015/03/human_integration_design_handbook_revision_1.pdf

NASA, 2014
NASA. (2014). *Human integration design handbook (HIDH)* (NASA/SP-2010-3407/REV1). NASA.

NASA, 2017
NASA. (2017). *NASA Systems engineering handbook: NASA/SP-2016-6105 Rev2* (2nd ed.). NASA.

NASA, 2020
NASA. (2020). *The Artemis Accords: Principles for cooperation in the civil exploration and use of the Moon, Mars, comets, and asteroids for peaceful purposes*. https://www.nasa.gov/wp-content/uploads/2022/11/Artemis-Accords-signed-13Oct2020.pdf

NASA, 2023
NASA. (2023). *NASA spaceflight human-system standard, volume 2: Human factors, habitability, and environmental health* (Rev. D). https://www.nasa.gov/wp-content/uploads/2023/11/nasa-std-3001-vol-2-rev-d-with-signature.pdf

OECD, 2019
OECD. (2019). *The space economy in figures: How space contributes to the global economy*. OECD Publishing. https://doi.org/10.1787/c5996201-en

Schmauder & Spanner-Ulmer, 2014
Schmauder, M., & Spanner-Ulmer, B. (2014). *Ergonomie, Grundlagen zur Interaktion Mensch, Technik und Organisation*, Reva Bundesverband e.V.

Singla & Shirke, 2024
Singla, J. G., & Shirke, K. S. (2024). Virtual reality, augmented reality and its potential use case in space engineering. *Current Science*, *127*(2), 175. https://doi.org/10.18520/cs/v127/i2/175-181

Succini et al., 2024
Succini, L., Ciravegna, E., Celaschi, F., & Pasini, V. (2024). Responsible advanced design: Achieving sustainability through collaborative processes. *Temes de Disseny*, *40*, 92–111. https://doi.org/10.46467/TdD40.2024.92-111

Vakoch, 2012
Vakoch, D. A. (Ed.). (2012). *Psychology of space exploration: Contemporary research in historical perspective*. NASA. https://www.nasa.gov/history/history-publications-and-resources/nasa-history-series/psychology-of-space-exploration/

Wang, 2009
Wang, X. (2009). Augmented reality in architecture and design: Potentials and challenges for application. *International Journal of Architectural Computing*, 7(2), 309–326. https://doi.org/10.1260/147807709788921985

Zakoyan et al., 2024
Zakoyan, N., Grizzaffi, L., Sindoni, E., Cambertoni, R., Rocci, L., Succini, L., Sicklinger, A., Pasini, V., & Montemurro, R. (2024). Sustainable Life Beyond Earth. How to Enhance Habitat Comfort for Space Travelers. *Responsible Space for Sustainability*. IAC 75th - International Astronautical Congress, Milan. https://doi.org/10.52202/078382-0055

DIGITAL DESIGN
FOR ADVANCED INTERACTION

DIGITAL DESIGN FOR ADVANCED INTERACTION

In the *Digital Design for Advanced Interaction* cluster, the advancements of Projects 1.2 *Advanced Virtual Tools for Digital Acquisition and Visual/Haptic XR Interaction for the Textile Industry* and 1.4 *Digital Services for Made in Italy: Digital Twins for Predictive Models and to Support the Lifecycle of Fashion Products* are presented.

Project 1.2 is articulated through three contributions. The first, "A Reliable, Affordable, Low-cost, and Open-source Tool for Fabric Surface Acquisition for the Textile Industry," describes the development of an optimized, low-cost workflow for the digitization of fabric samples in small and medium-sized textile companies. Meanwhile, "Haptic Perception and Enhancement of the Interactive Textile XR Experience" delves into the development of the digital material library, highlighting both physical fabric storage and related digitization methods, and illustrating experiments of virtual fabric manipulation experience.

Finally, "Next-Gen Textile Industry: from Digital Acquisition to Displacement Mapping," explores the creation of virtual twins of textile samples from normal map images, aimed at their integration into VR and AR environments for haptic and visual exploration of materials.

Project 1.4 is represented by two main contributions. The essay "Artificial Intelligence and Extended Reality in Fashion: Creativity and Heritage Preservation in the 2D-3D Transition" analyzes the transformative impact of AI and XR in the fashion industry, with a focus on enhancing creativity, heritage preservation and user engagement. In conclusion, the paper "Grounding Future Scenarios of Technology-Enhanced Fashion Heritage: a Preparatory Study for the Storytelling of Made in Italy" focuses on defining the potential applications of digital twins in the design, production and marketing of fashion products of Made in Italy brands, outlining innovative scenarios for heritage enhancement through emerging technologies.

A RELIABLE, AFFORDABLE, LOW-COST, AND OPEN-SOURCE TOOL FOR FABRIC SURFACE ACQUISITION FOR THE TEXTILE INDUSTRY

Riccardo Foschi, Federico Ponchio**, Paolo Cignoni***

1. Introduction

1.1. Circular and Sustainable Made in Italy

This research was developed in the context of the "Advanced virtual tools for digital acquisition and visual/haptic XR interaction for textile industry," Spoke 1 of the extended partnership of the PNRR project *Made in Italy Circolare e Sostenibile* (MICS) [MICS, 2023], (Progetto n. PE 00000004/PE11) that deals with the textile industry sector of Made in Italy (e.g., fashion, clothing, garments, shoes, furniture, automotive, etc.). The project 1.2 aims to develop workflows and implement low-cost advanced tools aimed at the small and medium industries operating in the textile industry sector of Made in Italy for collaborative remote design in XR (Extended reality). The first objective of the spoke is to develop an acquisition pipeline for the low-cost digitization of fabric samples, with high perceptual accuracy, without the need for specific expensive and proprietary technology. The second objective is to enable interaction with the digitized fabrics in a virtual environment through visual and haptic feedback. Lastly, the spoke aims to develop an open-access web infrastructure for cataloging, querying, sharing, and reusing digitized samples. All these three objectives come from the shared ambition to democratize the digitization process, without sacrificing the quality and accuracy of the result, and develop low-cost advanced solutions for interaction in XR, that would contribute to improving the competitiveness of the small-medium industry of Made in Italy.

**Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

***ISTI - CNR, Italy*

1.2. Fabric digitization

In this paper, we present the results of a minor part of the wider PNRR project. In particular, we will focus on the fabric digitization workflow and the implementation of the software responsi-

ble for the elaboration of the raw data and post-processing of the acquired samples. The open-source software Relight (Ponchio, 2024), originally developed by the CNR of Pisa for RTI acquisitions in the field of cultural heritage, has been implemented to make it suitable for the acquisition of fabric surfaces (and also other materials) and the elaboration of texture maps (e.g., albedo, normal map, height/displacement map, alpha map, translucency map) usable in most render engines and virtual environments.

2. Material digitization and software development

The digitization of physical materials requires:

- To capture several images under varying view direction and/or lighting conditions;
- To select a mathematical model for its representation and to fit the parameters to the measurement;
- Optionally to manually adjust the resulting maps in post-processing.

There is a wide range of possible configurations in each of these steps. Image acquisition usually requires specialized hardware, usually a dome, but handheld lights and cameras in various configurations can be a viable solution, maybe using a single viewpoint, up to the extreme solution of capturing a single photo.

Similarly many different mathematical models can be used, from the simpler analytical functions such as the Phong model with diffuse, specular components, to the more complex physically based models such as the CookTorrance (Guarnera et al., 2016). In particular, a class of mathematical models suitable for single viewpoint relighting images representing the reflectance as a linear combination of basis functions can faithfully reproduce complex materials albeit with the important single viewpoint limitation and limited post-processing capabilities.

Finally, the post-process editing of the dataset is usually required to create for example tileable maps, to tune the parameters to a specific rendering pipeline, or to remove artifacts or geometric deformations caused by uncalibrated acquisition.

2.1. State of the art on software

At the moment the number of solutions available in terms of hardware and software are very limited. Software packages developed for research purposes that are public, maintained, documented, robust, and user-friendly are unfortunately missing. The few commercial solutions available adopt proprietary software, dedicated (and expensive) hardware, and generally are not very flexible for example in the number of lights, models, and formats adopted or post-processing options.

Three main options to digitize physical materials exist material scanners, material authoring and 3D capture software, and outsourced scanning services. The material scanners—e.g. Tac7 (X-RITE & PANTONE, 2024), xTex (VIZOO3D, 2024)—require space-consuming and expensive dedicated hardware which is often specialized for that single task; and has a predetermined sample acquisition size; the software is often a black box, which limits versatility and verifiability; and can output proprietary formats which guaranty the highest possible accuracy but are compatible only with a specific set of render engines. DIY scanners exist but this approach requires a certain level of specialization in order to build the scanner—e.g. light dome, lightbox—and calibrate the workflow, which is cumbersome and time-consuming. Commercial material authoring and 3D capture software—e.g. Substance Sampler (ADOBE, 2024b), Substance Designer (ADOBE, 2024a), Knald (TECHNOLOGIES, 2024)—are cheaper solutions compared to commercial material scanners because they do not require any special hardware. However, they are often subscription-based, suffer from the same black-box problem mentioned before, and do not always allow for the calibration of the acquisition process. Concerning free and open-source apps—e.g. Details Captures (VFXGRACE, 2024), four light simple (RESEARCH INSTITUTE TECHNOLOGY, 2014)—they could be good low-cost solutions, for some uses, although they often implement dated algorithms, which would not always output robust and reliable results, are not always compatible with all operating systems, do not allow for simple calibration, impose a predetermined number of input pictures, or do not implement a user-friendly interface. For all these reasons they cannot be always used in an industrial environment, where not only the cost but most importantly quality

and reliability are key aspects. In the outsourcing scanning services—e.g. Chaos Scans (Chaos, 2024)—the samples must be physically shipped, this process requires time, and even though it is the only solution that does not require any specialization for the company that requests the service, in the long run, for a relevant number of acquisitions, the cost per-sample might be higher than buying a dedicated scanner.

2.1.1. RelightLab

Given these premises, we aim to develop RelightLab (Ponchio, 2024) as a more affordable, versatile, and flexible solution, that will be compatible with various workflows.

The software, hosted on GitHub, is free and available on all platforms (Windows, macOS, Linux). Thanks to the Open Source philosophy, it will be affordable for everybody and the community will help maintain, document, test, and support it through forums and developer contributions.

The software enables flexible acquisition planning because it supports light domes and hand-held lights with reflective spheres, or SALA-Frames (see Section 3.1), it also provides tools for acquisition support (e.g. image registration, reflective sphere auto-detection, white balance correction).

The software is designed to be extensible concerning the mathematical models supported: new fitting algorithms and BRDF are planned in the near future and should be easy for researchers who want to use this software for experimentation to add new fitting models.

The user base is going to be very diverse in terms of computer literacy and planned usage, ranging from plain end-users interested in the actual result of the digitization process to researchers willing to experiment with new workflows and models. For this reason, we provide a user-friendly graphical interface to guide the user in processing the datasets, and, at the same time, we provide scripts, command line executables, and reasonably stable API, to integrate the functionalities of this software in any workflow.

Finally, the workflow will be transparent and accessible: every parameter in each step of the processing and intermediate assets will be open for customization, editing, and verification.

2.2. Standards

Standard formats for relightable images do not exist. Some old and currently unmaintained early software established a de facto standard for the representation of Polynomial Texture Maps and Hemispherical Harmonics. This format however lacks many desirable features such as metadata storage (such as the EXIF mechanism in JPEG), lossless compression, and transparency, and they are inconvenient to parse and edit. Moreover, they are not suitable for web delivery: no support for progressive or multi-resolution tiled rendering, mostly because these formats were developed far before WebGL (required for RTI rendering) was developed.

Similarly, there is no standardization on the details of the model fitting algorithm, nor on the visualization equations and parameters for enhanced visualizations such as the specular enhancement mode which renders the surface as an extremely shiny material. The result of this situation is that starting from the same dataset different software will generate different renderings. The same phenomenon is happening for the more common BRDF acquisition and rendering software, in particular, due to the large number of existing analytical BRDF models with small variations adopted by different engines.

New mathematical models for relightable images have been developed in the last few years (based on principal component analysis and neural networks), and we can expect that others will be developed. New formats to represent them and efficiently share them on the web have been created in the RelightLab library, but we think that an effort to create a widely accepted standard would be important.

The International Image Interoperability Framework (IIIF) (Snydman et al., 2015), is a standard that enables the sharing and viewing of high-resolution digital images across different platforms. It provides a set of APIs for accessing images, metadata, and other related resources, allowing institutions to present, compare, and interact with images from diverse sources in a consistent and interoperable manner. This is particularly useful in cultural heritage and research contexts, where institutions can share their digitized collections globally while ensuring they can be accessed and used in a standardized way.

An accepted standard would create a small software ecosystem of tools that can cooperate. This makes it easier to develop a single tool (not having to provide the entire pipeline), and users won't suffer from vendor lock-in for lack of compatibility.

Inside this organization, we have created a charter initiative to standardize the delivery and rendering of relightable images and other 2D datasets that require substantial processing in the client such as multi-spectral datasets, where ReligthLab will offer a reference implementation.

3. Acquisition workflow

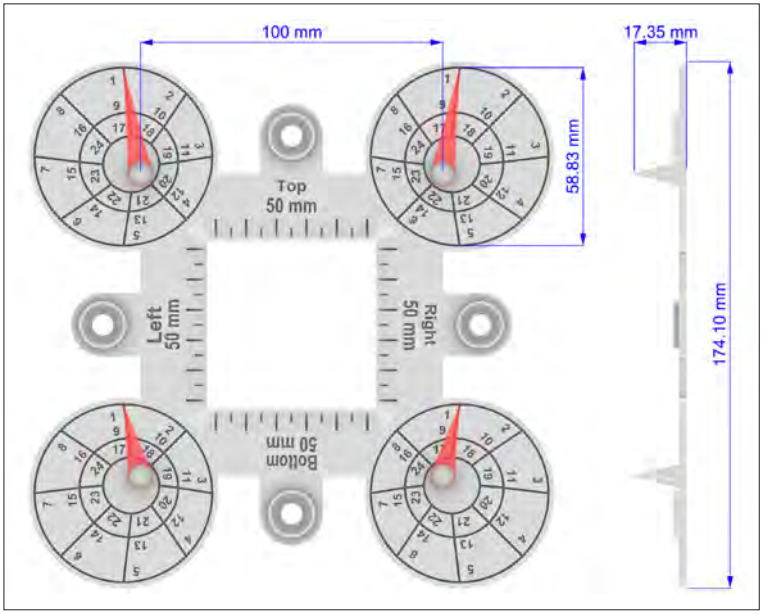
The acquisition workflow in RelightLab can vary based on which methodology is adopted (Light Dome, free handheld light positioning, SALA-Frame), nevertheless, the following steps are common to all methods:

- Image Capturing;
- Photo Alignment/Image registration;
- Setup Calibration: Detection of Light and Camera positions;
- Mathematical model choice (RTI /BRDF (ToDo)/Normals);
- Normal map post-processing (flattening/decomposition/ 3D reconstruction).

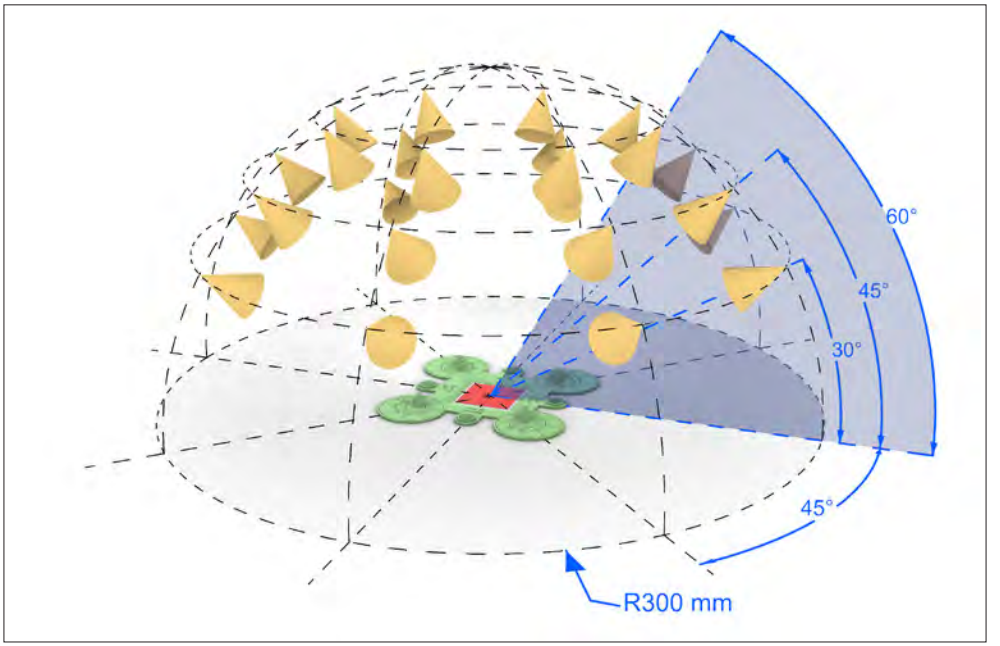
3.1. Image capturing

The digitization process starts by acquiring a set of pictures of a physical sample. In this chapter, we focus only on fabric samples but the same workflow could be followed to digitize a much wider variety of materials. The RTI or photometric stereo workflows (both supported by RelightLab) require the same photographic setup, namely: a fixed sample (fabric), a fixed point of view (camera), and a movable light source in a dark environment. Most commercial RTI scanners rely on a hemispherical dome of lights (FlyDome, 2023) or a lightbox (Vizo03d, 2024), however, to cut costs the source of light can be moved manually without relying on any dome-like structure. This solution is certainly less time-efficient but is readily available for everyone because it is inexpensive. In Relight-

Lab both hypotheses are supported (fixed lights, or hand-held lights), this choice increases the versatility of the tool but requires slightly different workflows. Since one of the aims of the project was keeping the costs low, in this paper we only focus on the image capturing through the use of a hand-held light that implies that the position of the light would change from one acquisition to the other. In this scenario, it is necessary to adopt certain precautions in order to calibrate the system. The most popular solution is to extrapolate the light position automatically for each picture, and it can be done by capturing together with the sample also one or more specular-reflective spheres (Li & Furukawa, 2015), this would allow us to infer the position of the light for each picture by isolating the specular highlights on the spheres and derive the direction of the light (and eventually, the distance if more than one sphere are used) by applying simple trigonometry. The reliability of this method depends on many factors. In particular, this method requires using small light sources and demands relevant manual work for the individuation of the spheres in the pictures and the visual verification of the correct guessing of the specular highlights. Furthermore, the fact that the spheres must be in frame reduces the area that the sample can occupy and thus its final resolution (especially because spheres must be far enough from the sample to prevent shadows from being cast on the sample). Moreover, if the lights are not distributed evenly on a hypothetical hemisphere centered in the sample it might produce unexpected results or aberrations. To reduce the variability of the distance of each light, a possible solution, previously tested by us, was to tie a rope to the light and extend it toward the sample before taking each picture (Zannoni et al., 2024), however, this increases the risk of touching and moving the sample invalidating the acquisition, and still does not solve the problem of angular distribution around the sample. For this reason, we developed a custom 3D printable Shadow Aided Light Alignment Frame (SALA-Frame) with four cones of known height, placed at the four corners, that act like gnomons, and aid the operator in the positioning of the light for each shot through the alignment of the tip of the cast shadows with four circular grids (fig. 1).



1. SALA-Frame top and side views. The four shadows of the cones are cast by a point light placed at 30° from the plane and 30 cm from the center of the frame. The numbers on the circular grids indicate the order in which the pictures must be captured. Four 15 mm ball bearings can be optionally placed on the circular bases at the cardinal axes for calibrating the setup. All images are reproduced in color in the online edition of the book.



2. Distribution of lights for the acquisition of a 50x50 mm sample using the SALA-frame.

Aligning all four shadow tips with the correct points on the circular grids is only possible when the light is on a predefined precise spot in 3D space. Bigger cones and grids enable more accurate alignment but require a larger frame (and vice versa). The SALA-Frame does not have to be entirely framed in the picture (or framed at all) since it is only needed to aid the light placing at the capturing phase and not at the post-processing phase. This allows us to maximize the effective resolution of the acquired sample and does not require deriving the positions of the lights through highlights on spheres making the preliminary processing as fast as using a predefined dome. The accuracy of the positioning of the lights depends on the operator but, based on empirical testing, it was estimated, on average, in the order of a few millimeters on a sphere of radius 30cm, which is more than enough to guarantee a high-quality acquisition in this context. The light positioning relative to the SALA-Frame is shown in figure 2.

The Frame was designed to fit a 200x200 mm standard 3D printer plate to make it more easily printable with consumer low-cost 3D printers, given this constraint the maximum sample size and the height of the cones were carefully calibrated to avoid casting shadows on the sample, resulting in a 50x50 mm sample area. When bigger samples need to be acquired it is always possible to scale up the frame or to use the reflective spheres and unaided hand-held light placement. Concerning the light source, with this setup, the lights are distributed on a 300 mm radius sphere, which can fit under most standard three-legged tripods (fig. 3), a bigger sphere might have resulted in a more difficult tripod setup. The minimum dihedral angle of 30° from the light direction and the plane was chosen to prevent the frame from becoming too big and to avoid self-shadowing in samples with relevant superficial displacement. With this method, it is preferable to use small lights because they cast sharper shadows and allow for an easier and more accurate alignment with the grid. When using domes that mount multiple light sources, the problem of acquiring a color-calibrated sample is not a trivial problem to solve because each light might vary in terms of intensity and color temperature. By using a single hand-held light this problem is mitigated because it would always have the same intensity and color temperature. Given

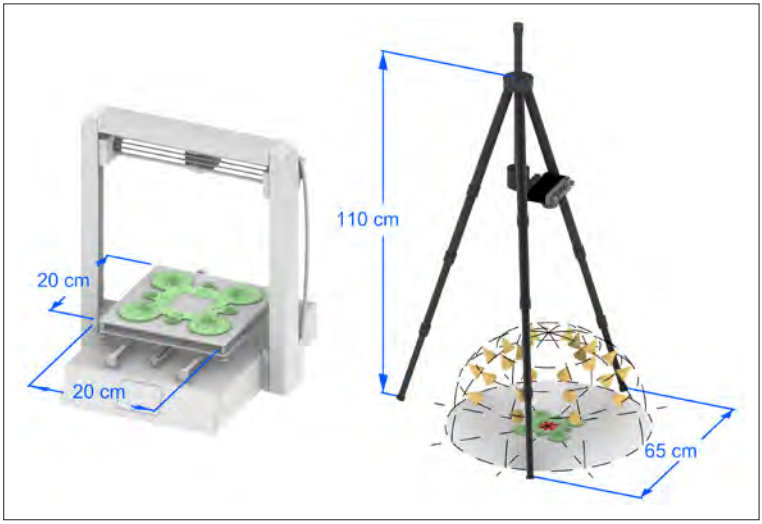
these premises, when using the SALA-Frame, the flashlight of any smartphone is a perfect solution for this task because they usually are close to neutral white and with a single shot to a color checker (or a more budget-friendly neutral grey card) before the acquisition campaign, it is possible to calibrate the colors of the whole set.

With this setup, it is possible to acquire the base color of the sample without shadows and glossy reflections (albedo map) and the geometric displacement of the surface up to high-frequency details (normal map, height/displacement map). For the acquisition of the translucency map and/or alpha mask it is sufficient to acquire a properly exposed back-lit picture of the sample, (any tablet display at maximum brightness with a white background can be used as a light source, to avoid moirè effects it is preferable to place a translucent paper between the display and the sample). Roughness and metalness properties are at the moment assigned via qualitative visual comparison, more work is needed to implement a procedure capable of extracting roughness and metalness maps automatically. Figure 4 shows an example of a set of 4 pictures and relative texture maps calculated with RelightLab, it also demonstrates that for diffusive simple materials like the one in the picture, it is not necessary to input 24 photos but 4 are enough. Lastly, it shows that the normal map calculated via SALA-Frame is much more accurate (the overall planarity of the surface is already achieved with no need to apply a flattening in post-production).

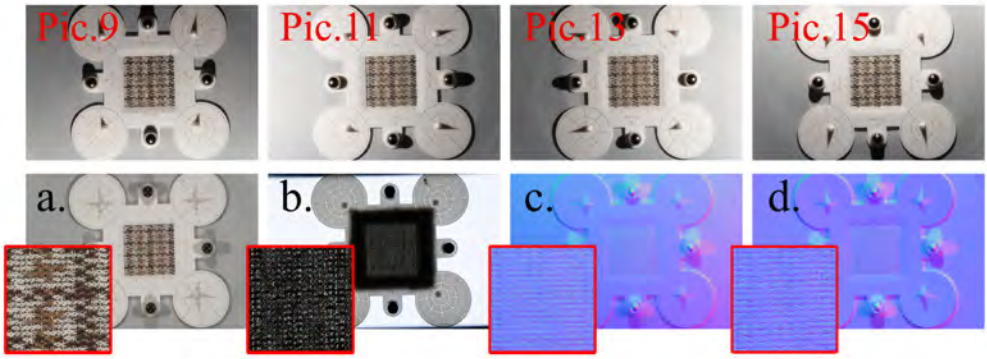
3.2. Image registration

One of the essential requirements for material acquisition is that the various images are perfectly aligned to create crisp texture maps and normal maps. Unfortunately, due to the high resolution of the modern cameras even small vibrations of the setup, often unavoidable, will result in several pixels of alignment error.

Image alignment has been developed for panorama generation or satellite imagery fusion, but the varying illumination makes the problem much harder to solve. Edge detection algorithms in particular suffer from the fact that all the shadows of the images (easily detected and usually the most prominent edges) will move together in the opposite direction of the light



3. SALA-frame fitting in a consumer 20x20 cm 3D printer and under most standard photographic three-legged tripods.



4. Top: pictures 9, 11, 13, 15 of the set of 24 photos. Bottom: texture maps calculated with RelightLab: a. albedo, b. translucency/alpha, c. normal map based on light position guessing via identification of highlight on shiny spheres, d. normal map via SALA-Frame; c. displays a gradient from cyan (left) to pink (right), indicating an overall bulging normal map. In contrast, d. exhibits no aberration, and the expected overall flatness is maintained.

tricking the algorithm into aligning the shadows instead of the objects.

Two strategies for image alignment under varying light conditions have been explored in the literature. The first approach (Berkiten & Rusinkiewicz, 2014) relies on feature detection (SIFT) similar to a Structure-From-Motion (SFM) approach. A second approach instead focuses on global image correlation employing a low-rank affine registration technique. We have integrated this second approach in RelightLab. Additional work is needed in terms of testing, optimization, finding suitable heuristics for the parameters and finally developing a user interface for verification of the result and eventually manual adjustments.

3.3. Setup calibration

Most of the existing software makes a strong simplification assuming lights come from an infinite distance such that they are constant for each pixel of the image. This approach results in strong warping of the normal map and uneven model re-illumination, and these problems are enhanced if the lights are relatively close to the subject. Warping effects can be corrected in a post-processing step, but having correct light geometry processing makes this step redundant.

Correct computation of the material characteristics from the images taken under different lighting requires that the lighting (position and intensity of the lights) be known. Once this is known either through dome geometry, reflective spheres, or SALA-Frame we can compute, for each pixel, the true light and intensity expected of each light. RelightLab supports an efficient per-pixel lighting computation.

3.4. Mathematical model choice

Many mathematical models to represent material appearance exist (Guarnera et al., 2016). RelightLab supports two use cases: single viewpoint visualization of relightable images and 3D visualization of textured 3D models. The first case, also known as Reflectance Transformation Imaging (RTI), is a bidimensional dataset composed of a certain number of images that can be used to modify the lighting of the dataset interactively. Several mathematical models based on polynomials, Polynomial Tex-

ture Maps of PTM (Malzbender et al., 2001), HemiSpherical Harmonics (HSH) (Gautron et al., 2004) or Radial Basis Functions (RBF) (Ponchio et al., 2019) and a few others, most of which are currently supported. RTI is used to quickly display the appearance of an object/textile, albeit from a single point of view, and can capture a large set of materials and effects. If we plan instead to use the material for 3D rendering we need to compute a set of textures as the parameters of a Spatially Varying Bidirectional Reflectance Distribution Function (SVBRDF). See figure 5 for a comparison between the real sample and the digitized version rendered in Blender.

Again many SVBRDF models with variants exist, thus we will focus on Physically Based Rendering (PBR) approaches. As an example, the model used in glTf 3D format relies on:

- Alpha Coverage: in textiles can be recovered using a backlight (converted in black and white and properly exposed);
- Translucency: in textiles can be recovered using a backlight (RGB map properly exposed);
- Base Color: can be extracted from RTI models;
- Emissive: probably not needed in textiles;
- Normal: already supported;
- Metallic: to be implemented (but can be already manually approximated using the same component in RTI models;
- Roughness: to be implemented.

This list has to be intended only for exemplification purposes, different software packages use different workflows (e.g., metalness/roughness, specularity/glossiness) and implement different texture maps.

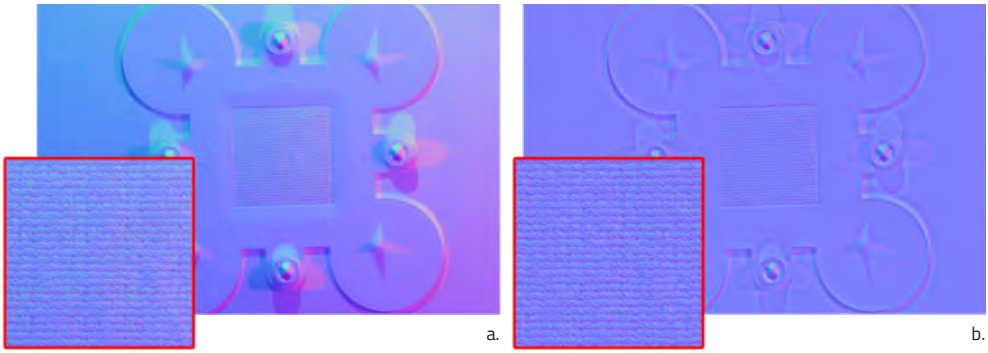
3.4.1. Export

If the mathematical model is an RTI, a few file formats are available for storing the results (see Section 2.2). Legacy .rti and .ptm are supported by software implementing several algorithms for inspection, analysis, and enhancement of some material characteristics (Palma et al., 2010), such as the unsharp mask. Alternatively, the dataset can be exported in a format easily shared on the web and rendered using a JavaScript library, this is a simple way to share material appearance on the web without



a1. b1. a2. b2.

5. a. Real sample, b. acquired sample rendered in Blender Cycles. 1. Silky synthetic silver colored fabric (acquired with 24 light points), 2. Jersey fabric with a white and brown motif (acquired with 4 light points). Albedo, Normal, and translucency maps were calculated with RelightLab, and roughness and metalness were guessed by visual comparison.



a. b.

6. a. Normal map calculated via highlight individuation on shiny spheres which presents visible aberration (a gradient from cyan to pink on the flat table), b. flattened normal map (high/low-frequency details decomposition), the flattening was exaggerated on purpose to make the effect more visible.

resorting to 3D modeling. For other BRDF models, the export is simply in the form of images.

3.5. Normal map post-processing

RelightLab generates the normal map with a simple algorithm looking for the axis of symmetry in the reflectance function, a reasonable assumption for most materials. The SALA-Frame method enables uniform light sampling on the hemisphere ensuring that the normal map is computed with good accuracy. We added post-processing tools to flatten the normal map, which is required if the geometry of the lights and the image plane is not known with sufficient precision or other factors such as ambient light. This kind of aberration is strongly mitigated when using a calibrated dome or SALA-Frame. Similarly, we allow the user to decompose and control the frequencies of the normal map so that for example the user can remove undulations in textile samples that are not perfectly flat which becomes important especially if textures are then mapped on a geometric model (fig. 6). A depth map can be extracted from the normal map, to create displacement maps, which is often useful for 3D sculpting purposes. This can be useful for materials with important geometric meso-structures.

4. Conclusion

In conclusion, a novel, low-cost, and robust methodology of material acquisition based on the use of an inexpensive 3D printable SALA-Frame and the implementation of RelightLab software were presented. The preliminary empirical tests on various data sets demonstrated that the methodology applied through RelightLab was able to produce high-quality results in all tested scenarios. Concerning free uncalibrated handheld acquisition with light direction guessed through the extrapolation of highlight on shiny spheres, the normal map presents aberration mainly due to inaccurate guessing of the light positions and disuniform angular light distribution, however, thanks to the decomposition algorithm implemented in RelightLab it is now possible to compensate these aberrations in post-production. Concerning handheld light placement aided through the SALA-Frame, the normal map

presents minimal aberrations, comparable to those obtained via light dome, and does not require further post-production in most cases. High-quality albedo, alpha and translucency maps are successfully extracted with both workflows adopted. More work still needs to be carried out in order to extract automatically the missing PBR maps (e.g., metalness, roughness) and to convert these maps into tileable seamless textures, at the moment this last step is carried out in third-party software.

References

Adobe, 2024a
Adobe. (2024a). *Substance designer webpage*. Retrieved August 28, 2024, from https://www.adobe.com/products/substance3d/apps/designer. html

Adobe, 2024b
Adobe. (2024b). *Substance sampler webpage*. Retrieved August 28, 2024, from https://www.adobe.com/hk en/products/substance3d-sampler. html

Berkiten & Rusinkiewicz 2014
Berkiten, S., & Rusinkiewicz, S. (2014, July). Alignment of images captured under different light directions. *Technical Report TR-974-14*, Princeton University.

Chaos, 2024
Chaos. (2024). *Chaos scans webpage*. Retrieved August 28, 2024, from https://www.chaos.com/scans?srsltid=AfmBOop8xclyqqAituBqnx7vQANPaijxZXFOF

FlyDome, 2023
FlyDome S.A.S. (2023). *RTI Dome webpage*. Retrieved August 22, 2024, from https://www.rti-dome.com/

Gautron et al., 2004
Gautron, P., Kriv ́anek, J., Pattanaik, S. N., & Bouatouch K. (2004). A novel hemispherical basis for accurate and efficient rendering. *Rendering Techniques*, 321–330.

Guarnera et al., 2016
Guarnera, D., Guarnera, G., Ghosh, A., Denk, C., & Glencross, M. (2016). BRDF representation and acquisition. *Computer Graphics Forum*, *35*(2), 625–650. https://onlinelibrary.wiley.com/doi/abs/10.1111/cgf.12867

Li & Furukawa, 2015
Li, B., & Furukawa, T. (2015). Design and calibration of a 3D High-Resolution surface profiling system using photometric stereo. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. https://doi.org/10.1115/DETC2015-47734

Malzbender, Gelb & Wolters, 2001
Malzbender, T., Gelb, D., & Wolters, H. (2001). Polynomial texture maps. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (pp. 519–528).

MICS, 2023
MICS. (2023). *MICS Made in Italy Circolare e Sostenibile*. Retrieved July 24, 2024, from https://www.mics.tech/

Palma et al., 2010
Palma, G., Corsini, M., Cignoni, P., Scopigno, R., & Mudge, M. (2010). Dynamic shading enhancement for reflectance transformation imaging. *ACM Journal on Computing and Cultural Heritage*, *3*(2), 1–20. https://doi.org/10.1145/1841317.1841321

Ponchio et al., 2019
Ponchio, F., Corsini, M., & Scopigno, R. (2019). Relight: A compact and accurate RTI representation for the Web. *Graphical Models*, *105*, 101040. https://doi.org/10.1016/j.gmod.2019.101040

Ponchio et al., 2024
Ponchio, F., et al. (2024). *Relight webpage*. Retrieved August 28, 2024, from https://vcg.isti.cnr.it/vcgtools/relight

Research Institute Technology, 2014
Research Institute Technology, R. (2014). *Four-light imaging simple*. Retrieved August 28, 2024, from https://www.rit.edu/science/studio-scientific-imaging-and-archiving-cultural-heritage

Snydman et al., 2015
Snydman, S., Sanderson, R., & Cramer, T. (2015). The International Image Interoperability Framework (IIIF): A community and technology approach for web-based images. *Archiving Conference*, *12*(1), 16–16. https://doi.org/10.2352/issn.2168-3204.2015.12.1.art00005

Technologies, 2024
Technologies. (2024). *Knald webpage*. Retrieved August 28, 2024, from https://www.knaldtech.com/

VFXGrace, 2024
VFXGrace. (2024). *Details capture webpage*. Retrieved August 28, 2024, from https://www.vfxgrace.com/product/detail-capture/

Vizoo3d, 2024
Vizoo3d. (2024). *Xtex scanners webpage*. Retrieved August 22, 2024, from https://www.vizoo3d.com/xtex-hardware/

x-rite & PANTONE, 2024
x-rite & PANTONE. (2024). *TAC7 scanner webpage*. Retrieved August 28, 2024, from https://github.com/cnr-isti-vclab/relight

Zannoni et al., 2024
Zannoni, M., Foschi, R., Pucci, D., & Saponelli, R. (2024). An immersive haptic experimentation for dematerialized textile perception in collaborative design processes. *SCIRES-IT - SCIentific RESearch and Information Technology*, *14*(1), 129–146. http://dx.doi.org/10.2423/i22394303v14n1p129

HAPTIC PERCEPTION AND ENHANCEMENT OF THE INTERACTIVE TEXTILE XR EXPERIENCE

Michele Zannoni, Roberto Saponelli**, Diego Pucci*, Ludovica Rosato**

1. Introduction

The contribution presented below outlines the developments of the first twelve months of progress in "Project 1.2," which is part of the "Spoke 1" group,[1] encompassing projects with the goal of digitising processes. The resulting work aims to extend the possibilities offered by digital tools to make them applicable in strategic areas of Italian craftsmanship, which are currently entirely analogue and artisanal. This objective represents a significant challenge because the target sectors, namely furniture and fashion, exhibit complex dynamics, and compressed development timelines, and involve actors with highly refined technical skills and sensitivities, which are extremely difficult to replicate and satisfy. On the contrary, digital tools, due to their dematerialised nature, allow for a drastic reduction in the resources expended in the iterative processes typical of artisanal methods.

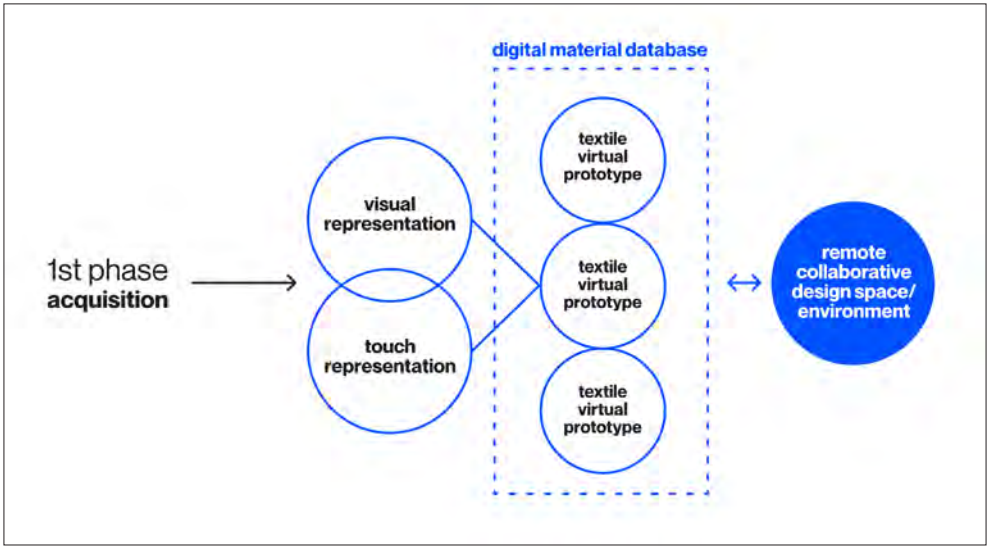
Therefore, this experimental research is founded at the intersection of the two worlds described, aiming to identify the boundary between what can be significantly simplified and virtualised in the textile world and what must remain analogue and exclusively within the domain of specialists. The work has been structured according to the workflow outlined in figure 1, which, following a dedicated acquisition phase, involves dedicated development, the subject of this progress.

2. Digital textile experiences for a circular and sustainable supply chain transition

**Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

***SACMI S.C., Imola, Italy*

In the process of material selection for textiles, the introduction of interactive digital experiences, for the fashion or furniture



1. Activities carried out within Project 1.2. All images are reproduced in color in the online edition of the book.

system, allows the creation of new sustainable and circular design possibilities for impact-critical fields of application.

The fashion system is characterised by a process of pre-production, production, distribution, use and disposal that produces harmful environmental and human impacts (Vezzoli et al., 2022). The fast fashion supply chain negatively impacts the use of water, land and resources by actively participating in climate change (European Environment Agency, 2022); it accounts for 3 to 10% of global emissions and, in Europe, is estimated to lead to the production of 15 kg of textile waste per person per year, with 85% of the total coming from post-consumer textiles (McKinsey & Company, 2022, p. 13).

However, textile waste is also generated in the pre-production phase, from the acquisition of resources through to their transformation into materials and into clothing products. The selection process of a material takes place in the pre-production phase and contributes differently to the production of emissions (Pellizzari & Genovesi, 2021). The prototyping phase involves physical sampling of the model to be put into production, for which the apparel industry invests between 5 and 7 billion pounds annually (Roberts-Islam, 2019). This sampling phase results in the creation of prototypes that are assembled and photographed for trend projection and evaluation. Brands and retailers continually require the creation of hundreds of new mock-ups which, inevitably, have a short shelf life and most end up being incinerated or disposed of in landfills, participating in the production of supply chain waste.

The distribution of samples also has an environmental impact in terms of transport, packaging and all sales and storage activities by suppliers (Vezzoli et al., 2022). The environmental impact of transport can vary according to the distance of the journey and the means of transport used; that of packaging according to the waste produced by primary, secondary and tertiary packaging. Overall, the environmental effects at this stage include the depletion of fossil resources, climate change, human toxicity due to air pollution and winter smog (Vezzoli et al., 2022). In the furnishing system, which is particularly critical in terms of transport related to product weight, Cerulo et al. (2022) suggest reducing these impacts by preferring local materials and solutions while minimising transport or identifying

transport solutions with minimal pollution by avoiding planes and trucks.

In Italy, this type of impact, applied to the Made in Italy system for fashion and furniture, is often limited by district policy and, therefore, the proximity of sub-suppliers in the entire production chain. However, when it comes to textile sourcing, this proximity is not always possible as their production is international (Textile Exchange, 2022).

Digitising the pre-production process, starting with the design and selection of the material is an action that could therefore offer a net reduction in resource use and textile waste production (Roberts-Islam, 2021).

3. Haptics and applied immersive experiences: State of the art

The digitalisation of processes is a practice in continuous expansion, particularly in the last two decades, where this phenomenon, taking advantage of highly sophisticated touchpoints resulting from advanced studies and experiments, has gained favour with specialised audiences. This allows for a reduction in the time needed to perform activities while simultaneously containing costs in terms of human and material resources. This refers to enabling technologies that can be broadly categorised into four families: data-driven, execution-driven, organisational-driven, and simulation-driven (Qi et al., 2021). For the project presented here, the last family, which includes outcomes related to extended reality and, in particular, virtual reality, is of interest in the context of digitalising processes performed prior to production.

The approach of virtual reality, or VR, finds application in many fields: advanced visualisation contexts (El Beheiry et al., 2019), customised configuration (Bachvarov et al., 2017), and procedure simulation (Van Campenhout et al., 2020), supporting evaluation activities and facilitating selection processes. These are always forms of representation; however, in each field, the virtual agent enhances different characteristics. A notable example is the presence and increased comprehensibility of structures or the intelligibility of data by using scenes and inputs familiar to the user (Lee et al., 2020).

The project therefore aims to embrace the various intrinsic advantages of using virtual environments, primarily taking advantage of the extreme ease of modifying elements and surfaces within the scene, the safety of a risk-free simulated environment since it is fictitious and, finally, the minimisation of the loss of representativeness of human-object interaction, which is crucial when it comes to fabrics and derivatives in the fashion and furnishings sectors.

Having defined the intention to deepen the relationship between design experiences in the textile field and virtual environments, the research team questioned which aspects should be the focus of their efforts. On one hand, the need emerged to identify a low-budget acquisition flow that would allow for the capture of physical samples and the production of high-fidelity virtual counterparts. On the other hand, the perception of virtual materials became a particularly interesting topic, as in the textile world, specialists cannot do without direct and tactile interaction with the materials they intend to use. In this regard, during the investigation of the state of the art, a significant emphasis was placed on haptics, meaning the ability to "feel" materials through touch and the related systems and devices necessary for their simulation and the digital definition of their contours (Ceccacci et al., 2023).

This landscape offers multiple insights and solutions to add a physical dimension to experiences that are otherwise intangible by nature, thus manifesting a common goal of impressing stimuli on the users' skin and receptors that add meaning to the experiences. As a result, commercial products are emerging, typically in the form of garments (with vests, gloves, and helmets being the most common), capable of generating forces, pressures, and vibrations that resist or otherwise respond to users' actions. Alongside these options, various prototypes are being developed that aim to enhance the definition and precise manipulation of virtual objects (Ninu et al., 2013) or specialise in the representation of volumes and interactions in extended spatial environments (Gomi et al., 2024). In any case, the proliferation and progress observed demonstrate the potential and subsequent interest in this field.

Based on these findings, the possibility of introducing such qualities into the project immediately seemed intriguing, as it

represents not only an additional level of complexity but also a multiplier of the value and representativeness of the experience. This is evidenced by the work of (Ornati & Kalbaska, 2022), who used this approach to enhance the remote fruition of textile products during the COVID-19 pandemic. In this project, however, thanks to the ability to personally manage the acquisition process, the idea was to develop a workflow aimed not at the communication and distribution of products but at their actual design, to provide valuable support to designers during the ideation phase.

4. Interactive textile XR experience

4.1. Methodology

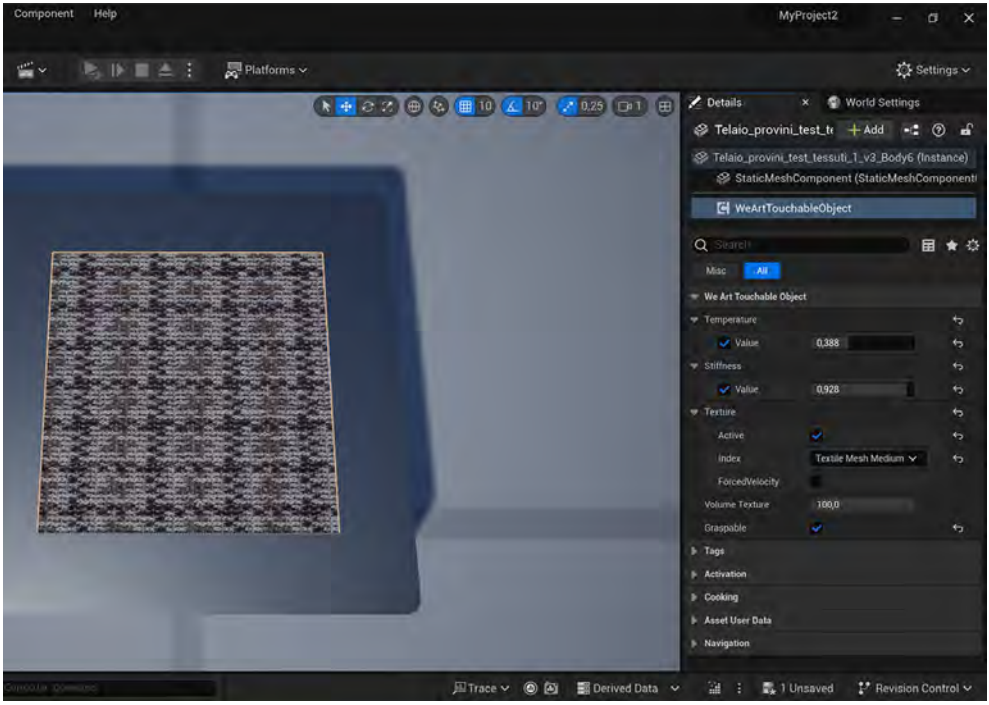
Starting from the project's ultimate goal, creating a set of advanced digital tools that support remote collaborative design processes, the target outputs to be achieved and the series of operations and activities necessary to reach them were defined. Three outcomes were hypothesised for the virtual design environment, which differs in complexity and priority within the developing workflow: the first involves inheriting the acquired virtual samples and categorising them in an archive potentially significant for stakeholders at the end of the process (fabric manufacturers, designers, and brands that market products containing the fabrics handled by the previous actors); the second, implementing tactile simulation parameters in the virtual textile models (figs. 2-3); and finally, following a specific experimental campaign, the definition of guidelines for the good design of remote collaborative design environments and contexts.

In the first half of the project, priority was given to the first two aspects, the details of which are the subject of the continuation of this contribution. In summary, following the first phase of research, a benchmark of possible software and hardware was conducted in parallel to study and design virtual experiences sufficiently effective, in line with the original project hypothesis, along with a field-specific verticalisation on the technical skills of the textile world, which was essential for preparing an archiving architecture consistent with the sector's needs.

2. Real textile sample.



3. Virtual Haptic textile counterpart.



User perception is a key issue in the selection of materials: it is the result of the interpretation of what is observed (Ashby & Johnson, 2010) and memory plays a key role as it records man's relationship with matter as it is transmitted to us (Manzini, 1986). Everyone has a different perception of the object based on his or her reaction to the physicality of the artefact and previous mental images of previously accumulated experiences (Ashby & Johnson, 2010). The perception and memory of material are formed from different characteristics that the object expresses: expressive sensory, association, perceptual and emotional, and technical functionality. The sum of these parameters forms the personality of a product (Ashby, 2010). The Material Experience (Karana et al., 2014), understood as the experience users have with materials through expressive-sensory characteristics, can be one of the variables of perception and personality of a material.

Understanding how to transition this experience into digital, translating the perceived characteristics into a comprehensible language and positively influencing its selection, is therefore a key variable in our design process.

While bringing this experience to XR and during the selection of material samples, an attempt was made to identify which parameters could be representative and in what way. Then, if we are talking about circular and sustainable materials for which research is directing its choices in the textile field but which, being many in the research phase, do not always have a recognisable material personality (Rosato, 2023).

The tests carried out so far simulate two main characteristics of the selection of fabric: temperature and touch sensation, allowing the perception of the "hand of the fabric." In particular, the haptic glove[2] used in the experiments makes it possible, through vibration and pressure, to simulate the sensations produced when a textile surface is handled through touch by running the fingers over the surface itself.

These two features are the first parameters studied and subsequent simulations of immersive experiences are being evaluated and studied.

4.2. Experimentations

To verify the perceived quality of the visual and tactile rendering of virtual fabrics, two test sessions were conducted, provid-

ing initial indications regarding the level of engagement of the virtual experience and the first ideas for reflection and modification.

The process of creating the experience evolved from the selection of fabric samples, choosing a range of options that balanced complexity with the fineness of the textures and the type of acquisition, whether through a commercial procedure (xTex Website, n.d.) or the workflow that is part of this project. Subsequently, a virtual scene was created, containing a frame that included the samples chosen for the test, and then the physical testing environment was set up, consisting of a computer, virtual headset, haptic glove, and real samples; figure 4 shows the setup.

The first series of preliminary tests involved seven non-professional figures with good experience and familiarity with the use of virtual tools, in order to speed up the selection of the most understandable experience flow and gather clear technical feedback and input to implement (Zannoni et al., 2024). In this first phase, it immediately became apparent that the different acquisition processes were not perceived as different by the testers, highlighting that the visual rendering of the samples is comparable and of good quality, at the point of influencing significantly the process of association between real and virtual samples.

Following the necessary implementations, the virtual scene was presented to another twenty testers, again non-professionals, without proven experience and familiarity with digital tools. Specifically, the participants were divided into two groups, with the common goal of associating the touch of the virtual material with the corresponding real fabric sample. The first group experienced a virtual scene where the virtual samples were visually identical and tactilely differentiated, while the second group's experience included both tactile and visual differentiation.

5. Discussion

The experimentation, representing the culmination of the work done so far, has yielded positive results in terms of understanding the scene and experience, demonstrating a good level of engagement and presence among the participants. However, the



4. Hardware test environment.



5. Association test between physical samples and digital ones without visual texture.

results did not fully validate the restitution process, underlining that there is still much work to be done in both the design of experiences and the technological refinement of tactile stimuli. On the other hand, the results are encouraging as they show the success of the acquisition procedure and demonstrate the feasibility of the remote collaborative design environment.

Summarising the findings from the investigation, the impact of visualisation is extremely relevant despite the focus being on touch. In the two groups studied, the percentage of correct associations between the virtual and real samples was significantly higher when the digital counterpart was visually textured, confirming the good usability of the acquisition output and that the visual-tactile virtual experience is converging, suggesting a reasonable representativeness of the system, as shown in figure 5. Another interesting factor that emerged is the impact of the testers' familiarity with the tools used. As initially hypothesised, those more accustomed to tactile stimuli generated by smartphones and gaming joysticks showed greater sensitivity and responsiveness to the haptic simulation used. The simulation still requires further implementation since the correct associations were derived from comparisons with only one real sample at a time, indicating that an unambiguous convergence between the real and digital textures has not yet been achieved, which remains a priority topic for further exploration in the project.

Other implementation fronts mainly involve conducting a couple of counter-tests to serve as a filter for a more nuanced and informed interpretation of the data collected so far. Specifically, a plan is in place to conduct the same test described previously with an additional variant, namely the association between real touch and only virtual visualisation, in order to determine whether the better results obtained when the virtual samples were differentiated are solely due to vision or if the tactile enhancement actually contributes to recognisability. Finally, there is also an intention to perform a test with expert specialists whose touch sensitivity is particularly well-trained, to understand whether the limited recognisability of the current tactile patterns is indeed lacking and thus requires a drastic rethink of the representation or if it involves minor variations that still need fine-tuning.

6. Conclusion

The experiments developed so far are preparatory to the realisation of the digital material database (fig. 1). This product aims to collect the digital models of textile samples of the Made in Italy companies in order, on the one hand, to facilitate the selection of materials to the operators of the supply chain through a platform that collects and archives the products in an organised way, and, on the other hand, to obtain the models for virtual prototyping. Moreover, the integration of the virtual fabric handling experience enables operators to obtain a complete material selection method, from the analysis of the technical characteristics communicated in the database, to their sensorial experience through XR, to their use for virtual prototyping.

The digital material library is a work in progress; to date, the research has traced the needs of the territory, both through desk research that helps to define the storage methods of physical fabrics and the corresponding digitisation methods, and through the mapping of the territory's supply chain, in order to highlight which actors and at what stage they enter into communication with the platform. Moreover, through field research, we involved local companies, and possible users of the service, in order to map and collect their needs both in terms of how to acquire and disseminate fabrics and in terms of end uses of the platform.

Notes

[1] Internal coding within the extended MICS partnership, which oversees the projects related to the "Made in Italy Circular and Sustainable," funded by PNRR national project.

[2] The device adopted for the virtual tactile representation of fabrics is the "WeArt Touch Diver," selected due to the good ratio between the range of stimuli it can generate and the complexity of the process. Additionally, the manufacturing company, based in Milan, reflects the Made in Italy character of the project.

References

Ashby & Johnson, 2010
Ashby, M., & Johnson, K. (2010). *Materiali e Design. L'arte e la scienza della selezione dei materiali per il progetto*. Casa Editrice Ambrosiana.

Ceccacci et al., 2023
Ceccacci, S., Gentilozzi, C., Marfoglia, A., Santilli, T., Mengoni, M., Capellini, S. A., & Giaconi, C. (2023). Haptic Feedback to Support the Conceptualization of the Shape of Virtual Objects: An Exploratory Study. In M. Antona & C. Stephanidis (Eds.), *Universal Access in Human-Computer Interaction* (pp. 215–228). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-35681-0_14

Cerulo et al., 2022
Cerulo, B., Papile, F., Motta, M., Marinelli, A., Conti, G. M., & Del Curto, B. (2022). 3D knitting for upholstery: Guidelines to design at the interface of sustainable fashion and furniture. In *Human Factors for Apparel and Textile Engineering. Proceedings of the 13th International Conference on Applied Human Factors and Ergonomics*, AHFE (pp. 129–137). https://doi.org/10.54941/ahfe1001547

El Beheiry et al., 2019
El Beheiry, M., Doutreligne, S., Caporal, C., Ostertag, C., Dahan, M., & Masson, J.-B. (2019). Virtual reality: Beyond visualization. *Journal of Molecular Biology*, *431*(7), 1315–1321. https://doi.org/10.1016/j.jmb.2019.01.033

European Environment Agency, 2022
European Environment Agency. (2022). *Textiles and the environment: The role of design in Europe's circular economy*.

Gomi et al., 2024
Gomi, R., Suzuki, R., Takashima, K., Fujita, K., & Kitamura, Y. (2024). InflatableBots: Inflatable shape-changing mobile robots for large-scale encountered-type haptics in VR. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (pp. 1–14). https://doi.org/10.1145/3613904.3642069

Karana et al., 2014
Karana, E., Pedgley, O., & Rognoli, V. (Eds.) (2014). *Materials experience: Fundamentals of materials and design*. Butterworth-Heinemann.

Lee et al., 2020
Lee, B., Brown, D., Lee, B., Hurter, C., Drucker, S., & Dwyer, T. (2020). Data visceralization: Enabling deeper understanding of data using virtual reality. In *IEEE Transactions on Visualization and Computer Graphics*, *PP* (pp. 1095–1105). https://doi.org/10.1109/TVCG.2020.3030435

Manzini, 1986
Manzini, E. (1986). *La materia dell'invenzione. Materiali e progetto*. Arcadia.

McKinsey & Company, 2022
McKinsey & Company. (2022). *Scaling textile recycling in Europe–turning waste into value*.

Ninu et al., 2013
Ninu, A., Dosen, S., Farina, D., Rattay, F., & Dietl, H. (2013). A novel wearable

vibro-tactile haptic device. In *2013 IEEE International Conference on Consumer Electronics (ICCE)* (pp. 51–52). https://doi.org/10.1109/ICCE.2013.6486791

Ornati & Kalbaska, 2022
Ornati, M., & Kalbaska, N. (2022). Looking for haptics. Touch digitalization business strategies in luxury and fashion during COVID-19 and beyond. *Digital Business*, *2*(2), 100035. https://doi.org/10.1016/j.digbus.2022.100035

Pellizzari & Genovesi, 2021
Pellizzari, A., & Genovesi, E. (2021). *Neo materiali 2.0 nell'economia circolare*. Edizioni Ambiente.

Qi et al., 2021
Qi, Q., Tao, F., Hu, T., Answer, N., Liu, A., Wei, Y., Wang, L., & Nee, A. Y. C. (2021). Enabling technologies and tools for digital twin. *Journal of Manufacturing Systems*, *58*, 3–21. https://doi.org/10.1016/j.jmsy.2019.10.001

Roberts-Islam, 2019
Roberts-Islam, B. (2019, October 2). *How 3D digital design and augmented reality can slash textile waste in fashion*. Eco-Age. https://eco-age.com/resources/how-3d-digital-design-and-augmented-reality-can-slash-textile-waste-fashion/

Roberts-Islam, 2021
Roberts-Islam, B. (2021). *How digital fashion could replace fast fashion, and the startup paving the way*. Forbes. https://www.forbes.com/sites/brookerobertsislam/2020/08/21/how-digital-fashion-could-replace-fast-fashion-and-the-startup-paving-the-way/

Rosato, 2023
Rosato, L. (2023). *Transition Matters. Il ruolo del designer nella transizione sostenibile e circolare dei materiali polimerici* [Doctoral dissertation, Alma Mater Studiorum - University of Bologna].

Textile Exchange, 2022
Textile Exchange. (2022). *Preferred Fiber & Materials Market Report*.

Van Campenhout et al., 2020
Van Campenhout, L., Van Camp, M., & Vancoppenolle, W. (2020). Exploring Tangible VR as a Tool for Workplace Design. In *Companion Proceedings of the 2020 Conference on Interactive Surfaces and Spaces* (pp. 33–36). https://doi.org/10.1145/3380867.3426202

Vezzoli et al., 2022
Vezzoli, C., Conti, G. M., Macrì, L., & Motta, M. (2022). *Designing Sustainable Clothing Systems*. Franco Angeli.

xTex Website, n.d.
xTex Website. (n.d.). https://www.vizoo3d.com/xtex-hardware/.

Zannoni, 2024
Zannoni, M., Foschi, R., Pucci, D., & Saponelli, R. (2024). An immersive haptic experimentation for dematerialized textile perception in collaborative design processes. *SCIRES-IT - SCIentific RESearch and Information Technology*, *14*(1). https://doi.org/10.2423/i22394303v14n1p129

NEXT-GEN TEXTILE INDUSTRY: FROM DIGITAL ACQUISITION TO DISPLACEMENT MAPPING

Gaia Ghidoni, Riccardo Foschi*, Martin Huska**, Serena Morigi***

1. Introduction

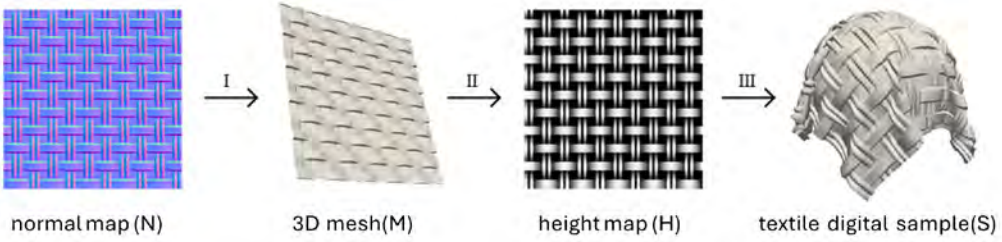
Replicating the tactile and visual qualities of real-world surfaces and objects is a priority for 3D visualisation and processing in many application fields. The convergence of research areas and the rapid development of scanning technologies (e.g., laser, structured light, photogrammetry, photometric stereo, reflectance transformation imaging software) have made it possible to create highly accurate digital representations of real-world surfaces, which have become invaluable in fields such as the preservation of artistic heritage (Fantini, Gaiani & Garagnani, 2023; Apollonio et al., 2021), architectural heritage (Pavlidis et al., 2007), manufacturing (Bi & Wang, 2010), games (Bourke & Green, 2016), medicine (Thali, Braun, & Dirnhofer, 2003) and so on. This work is placed in this context, as part of the research project *Advanced virtual tools for digital acquisition and visual/haptic XR interaction for textile industry*, Spoke 1, within the extended partnership of the PNRR project *Made in Italy Circolare e Sostenibile* (MICS) (MICS, n.d.) (Progetto n. PE 00000004/ PE11). The project deals with the textile industry sector of Made in Italy (e.g., fashion, clothing, garments, shoes, furniture, automotive, etc.), and aims to develop new scenarios for the integration of immersive technologies in traditional craft processes by producing low-cost digital acquisition and restitution process of textile samples useful for possible new advanced modalities of collaborative remote design in XR (extended reality). The project is divided into three main branches of research. The first one is aimed at the low-cost acquisition of fabric samples, with high perceptual accuracy. The objectives of the first research branch are to develop a calibrated and low-cost protocol of acquisition based on the photometric stereo technique, accompanied by a set of tools able to reduce as much as possible subjective adjust-

**Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

***Department of Mathematics, Alma Mater Studiorum - University of Bologna, Italy*

ments, arbitrary decisions, time consumption, and specialisation required for the digitisation phase while still guaranteeing consistent results for fabric samples at different sizes and with various fibre compositions. The second branch aims to enable interaction with fabrics in XR through visual and haptic feedback. The third branch deals with the creation of an open-access web infrastructure for cataloguing, querying, sharing and reusing the digitised samples. This work focuses on the research results achieved in the context of the first research branch. The low-cost acquisition photometric stereo technique recovers surface normals of an object (fabric sample) on a per-pixel basis from a set of images captured from a fixed viewpoint under various lighting directions. The focus of the research presented is the post-processing of the geometric raw data, in the form of normal maps, acquired through the preliminary acquisition procedure based on the photometric stereo technique, as explained in (Zannoni et al., 2024). The algorithms that are investigated and validated in this research will be later integrated into the software Relight (Ponchio et al., 2024) by CNR of Pisa with the aim of making it more versatile and suitable for producing PBR maps for the visualisation and the haptic-oriented immersive manipulation of the digitised fabric samples.

Figure 1 illustrates the main stages of the proposed work. The estimated surface normals are stored as an RGB image known as the *normal map* $\boldsymbol{N}$, shown in fig. 1 (left), where the RGB components correspond to the x, y, z components of the surface normal. In the first stage (I) the height field surface $\mathcal{M}$ is recovered from the normal map $\boldsymbol{N}$. The surface $\mathcal{M}$ is represented by a polygonal quadrilateral, regular mesh with a rectangular-shaped boundary. The second stage (II) reconstructs the height map $\boldsymbol{H}$ from $\mathcal{M}$. Height maps are grayscale images that represent the elevation of a 3D surface, with each pixel encoding the height value. The minimum height is represented by black pixels, while the maximum height is represented by white pixels. Finally, the displacement mapping allows for texturing a textile sample $\mathcal{S}$ by fitting the height map $\boldsymbol{H}$. Displacement mapping (Cook, 1984; Cook et al., 1987) is a well-known technique used in computer graphics to apply detailed geometric information, encoded in a texture image, onto a smooth surface (the object's macrostructure).



1. Stages of the project. From left: (I) height field surface recovery from the normal map; (II) height map reconstruction; (III) displacement map to a textile sample.
All images are reproduced in color in the online edition of the book.

2. Recover the 3D surfaces from normal maps

A normal map $\boldsymbol{N}$: $\Omega_n \rightarrow S^2 \subset \mathbb{R}^3$ associates to each point of the image $\bar{\boldsymbol{x}} = [u, v]^T$ the known outer unit-length normal vector $\boldsymbol{n}(u, v) = [n_1(u, v), n_2(u, v), n_3(u, v)]^T$, where $\Omega_n \subset \{1, \ldots, H\} \times \{1, \ldots, W\}$ is the image domain with dimensions $H \times W$.

Integrating the normal field $\boldsymbol{n}$, named normal integration problem, amounts to determining the functions x, y, z such that the normal at the point $\boldsymbol{p}(u, v) = [x(u, v), y(u, v), z(u, v)]$ on the 3D surface is equal to $\boldsymbol{n}(u, v)$. Under the assumption of orthographic projection, a 3D-point $\boldsymbol{p}(u, v)$ projects orthogonally onto the image plane, i.e., $x(u, v) = u$, $y(u, v) = v$. By normalising the cross product of both partial derivatives $\partial_u p$, $\partial_v p$ and choosing the sign so that the vector $\boldsymbol{n}$ points outward, we obtain $\boldsymbol{n}(u, v) = \dfrac{1}{\sqrt{1 + \|\nabla z\|^2}} [\partial_u z, \partial_v z, -1]$, where $\nabla z = [\partial_u z, \partial_v z]^T$ denotes the gradient field of the depth map z, with $\partial_u z$ and $\partial_v z$ being the partial derivatives. The normal integration problem aims to estimate the depth map z based on the pair of linear differential equations:

$$\nabla z = [p, q]^T, \quad p = -\frac{n_1}{n_3}, \quad q = -\frac{n_2}{n_3} \tag{2.1}$$

The surface can be reconstructed by integrating (2.1):

$$z(u, v) = z(u_0, v_0) + \int_{(r,s)=(u_0,v_0)}^{(u,v)} [p(r, s)\, dr + q(r, s)\, ds] \tag{2.2}$$

with (u_0, v_0) a point where z is known; in case there is no such a point, then $z(u, v)$ is computable up to an additive constant.

Denoting by $\boldsymbol{g} = [p, q]^T$ the datum of the problem, the *variational* normal integration method aims to solve (2.1) by minimising the following quadratic functional $\mathcal{J}(z)$:

$$\min_z \mathcal{J}(z) := \iint_{(u,v)\in\Omega} \|\nabla z(u, v) - \boldsymbol{g}(u, v)\| \, du\, dv \tag{2.3}$$

where $\Omega \subset R^2$ is the reconstruction domain. The functional $\mathcal{J}$ is strictly convex in ∇z, but does not admit a unique minimiser z^* since, for any $c \in \mathbb{R}$, $\mathcal{J}(z^* + c) = \mathcal{J}(z^*)$, see (Quéau, Durou & Aujol, 2017).

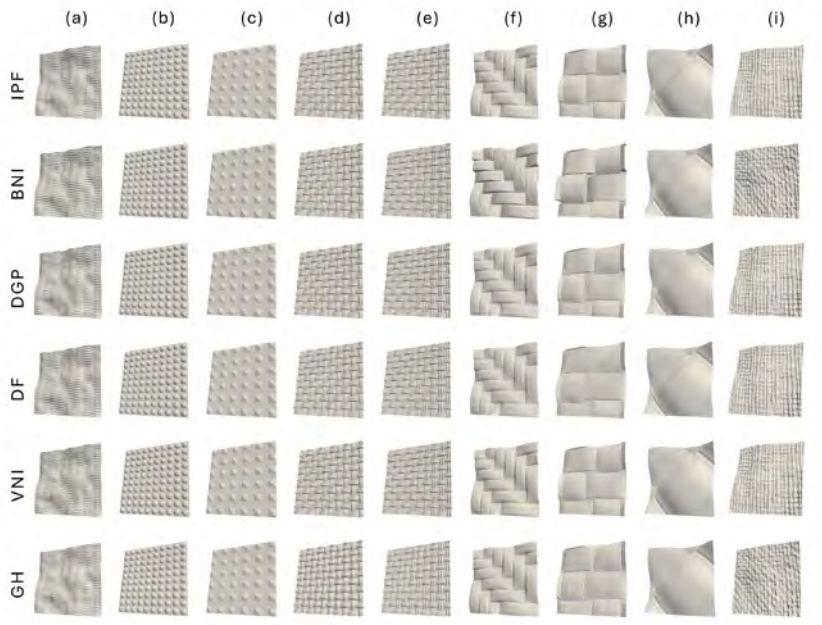
Various numerical methods have been proposed to address the problem of reconstructing a surface from its normal field. These methods aim to overcome the inherent challenges of the problem, often employing distinct solution approaches see (Quéau, Durou & Aujol, 2017). Among the tested variational methods, the Inverse Plane Fitting (IPF) method (Cao et al., 2021) formulates the normal integration problem as the inverse problem of *local plane fitting*, optimising point positions and local plane displacements in the camera coordinates. The Discrete Functional (DF) method (Harker & O'Leary, 2015) formulates the global least square cost function in terms of matrix algebra and solves the surface reconstruction problem using the Sylvester Matrix Equation. Authors of the Variational Normal Integration (VNI) method (Quéau, Durou & Aujol, 2018) propose a specific discretisation strategy for solving (2.3) that is independent of the shape of the domain.

Moreover, the Bilateral Normal Integration (BNI) approach (Cao et al., 2022) relies on preserving surface discontinuities when recovering it from its normal map. Under the assumption of one-sided differentiability of the underlying surface, the authors propose optimising a bilaterally weighted function to solve the normal integration problem. Furthermore, two additional methods were selected: the non-variational approach Discrete Geometry Processing (DGP) (Xie et al., 2014), which formulates the problem in terms of discrete geometry processing, and the algorithmic modelling solution Grasshopper (GH) (Apollonio et al., 2021).

2.1. Experimental results for stage (I)

The selected normal integration methods have been compared in the reconstruction of a set of input normal maps (illustrated in the first row of figure 2).

The normal maps (a)-(e) are images of dimensions 2048 × 2048 pixels with a colour depth of 64 bits, whereas the normal maps (f)-(i) are 512 × 512 pixels with a colour depth of 32 bits.



2. Qualitative comparison of reconstructed surfaces by normal integration methods. The input normal maps are presented in the first row; the subsequent rows show the reconstruction results of the tested methods, as indicated by the acronym at the beginning of each row.

The results were generated on a PC with Intel i7-7500U CPU with 2.67GHz and 12GB RAM. The BNI implementation code is publicly available at https://github.com/xucao-42/bilateral_normal_integration by the authors. They also provided implementation of the methods IPF, DGP, DF and VNI, which can be found at https://github.com/xucao-42/NormalIntegration. The implementation of the GH procedure was provided directly by the authors (Apollonio et al., 2021).

For each normal map image of $H \times W$ pixels, all methods produce a final regular quadrilateral mesh $\mathcal{M}$ of $H \times W$ vertices, except for the GH method. This method, constrained by the limitations of the modelling software employed, generates a grid mesh not exceeding 200 × 200 vertices.

A qualitative comparison of the obtained surfaces is presented in figure 2. Row-wise we report the recovered surfaces $\mathcal{M}$ achieved by applying the normal integration methods (listed in the rows) to the set of input normal maps $\boldsymbol{N}$. Methods IPF, DGP, DF, and VNI show visually similar results for normal maps (a)-(e), although DF exhibits a checkerboard artefact in the reconstruction of surfaces (see reconstructions of normal maps (d)-(g)). The BNI method performs best in reconstructing surfaces with discontinuities, as demonstrated in the details of the normal map (a). However, this method requires an accurate hand-tuning of the parameter value that controls the sharpness of the sigmoid function used for discontinuity preservation. The most significant differences can be observed in the reconstructions of the normal maps (f)-(h).

A quantitative evaluation of the compared selected methods is achieved using two popular metrics: the *Mean Square Angular Error* (MSAE) and the *Hausdorff Distance* (D_H). The latter is used only in case a ground truth surface is available.

Given the reconstructed surface as a polygonal mesh $\mathcal{M}$, the MSAE metric averages the deviation across all faces of the normal vectors $\boldsymbol{N}$ of $\mathcal{M}$ compared to the normal vectors $\bar{\boldsymbol{n}}$ represented by the normal map:

$$\text{MSAE} = \text{average}\left(\angle(\bar{\boldsymbol{n}}, \boldsymbol{n})\right) \quad (2.4)$$

where $\angle(\bar{\boldsymbol{n}}, \boldsymbol{n})$ represents the angle between the two normal vectors. Smaller MSAE values represent more accurate reconstructions.

The Hausdorff Distance measures the distance between the two 3D surface meshes $\bar{\mathcal{M}}$ and $\mathcal{M}$, where $\bar{\mathcal{M}}$ is the ground truth surface, based on the distance of each point $\bar{\boldsymbol{p}} \in \bar{\mathcal{M}}$ to the points $\boldsymbol{p} \in \mathcal{M}$. Denoting by $\delta(\bar{\boldsymbol{p}}, \mathcal{M}) = \min_{\bar{p} \in \bar{\mathcal{M}}} \|\boldsymbol{p} - \bar{\boldsymbol{p}}\|_2$, the distance between a point $\boldsymbol{p}$ belonging to a surface $\mathcal{M}$ and a surface $\bar{\mathcal{M}}$, the Hausdorff Distance is defined as follows

$$D_H(\bar{\mathcal{M}}, \mathcal{M}) = \max\left\{d(\bar{\mathcal{M}}, \mathcal{M}),\ d(\mathcal{M}, \bar{\mathcal{M}})\right\},$$
$$d(\mathcal{M}, \bar{\mathcal{M}}) = \max_{p \in \mathcal{M}} \delta(\bar{\boldsymbol{p}}, \mathcal{M}) \quad (2.5)$$

Smaller values of $D_H(\bar{\mathcal{M}}, \mathcal{M})$ indicate greater similarity between the two meshes $\bar{\mathcal{M}}$ and $\mathcal{M}$, with the minimum value being zero when the two surfaces coincide.

The quantitative results for both metrics, as well as the execution times, are presented in table 1. The D_H metric is inapplicable to reconstructed normal maps (f)-(i) due to a lack of ground truth. The evaluation of the D_H metric is normalised with respect to the length of the bounding box diagonal.

The quantitative analysis confirms the findings observed qualitatively. For the reconstruction of normal map (a) using the IPF method, slightly higher error values are observed compared to other methods. The increased Hausdorff distance can be attributed to inaccuracies in the reconstructed surface orientation, leading to deviations of many mesh points from the ground truth surface. While the remaining normal integration methods exhibit comparable results, the reconstruction errors vary depending on the specific input normal map.

Execution times reported in seconds in table 1 for IPF, DGP, DF, and VNI methods, are comparable. The BNI method exhibits substantial differences in execution time, influenced by both the size of the input normal map and the number of iterations necessary for convergence. The method's enhanced ability to handle surface discontinuities leads to increased accuracy but also results in longer processing times.

Based on the experimental results, we selected the VNI method as the more robust normal integration approach for the textile industry application.

Tab. 1. Quantitative comparison of the normal integration methods. The table reports the two metrics D_H and *MSAE*, as well as the execution time (*time*) in seconds for each normal map (a) – (i).

Method		Normal Map								
		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
IPF	D_H	0.0491	0.0097	0.0059	0.0053	0.0071	-	-	-	-
	MSAE	0.0060	0.0002	0.0001	0.0001	0.0001	0.0137	0.0155	0.0010	0.0021
	time	226	233	248	239	255	14	22	14	14
BNI	D_H	0.0344	0.0027	0.0024	0.0164	0.0122	-	-	-	-
	MSAE	0.0015	9.27e-7	2.21e-6	2.47e-5	3.12e-5	0.0043	0.0050	0.0010	0.0026
	time	1775	60	158	178	317	294	139	213	14
DGP	D_H	0.0143	0.0033	0.0055	0.0010	0.0021	-	-	-	-
	MSAE	0.0015	9.94e-7	2.93e-6	1.91e-5	2.59e-5	0.0140	0.0160	0.0010	0.0027
	time	153	136	166	139	148	8	9	8	10
DF	D_H	0.0134	0.0033	0.0054	0.0023	0.0012	-	-	-	-
	MSAE	0.0015	6.38e-7	9.86e-7	0.0010	0.0012	0.0143	0.0178	0.0006	0.0013
	time	109	124	125	156	97	7	8	7	8
VNI	D_H	0.0165	0.0033	0.0056	0.0012	0.0023	-	-	-	-
	MSAE	0.0015	9.14e-7	3.05e-6	1.98e-5	2.63e-5	0.0140	0.0160	0.0010	0.0026
	time	110	135	103	102	108	9	6	8	11
GH	D_H	0.2171	0.2001	0.1738	0.1542	0.0615	-	-	-	-
	MSAE	-	-	-	-	-	-	-	-	-
	time	75	80	70	72	83	60	57	62	55

3. Height Map generation from 3D surface meshes

In the second stage of the proposed framework, we consider the problem of recovering the height information from a given 3D surface. The height maps are suitable for the subsequent phase, which involves applying the geometric details of the fabric to a smooth-surfaced 3D object.

Considering the specific nature of the fabric textiles, the height map generation is produced under the following assumptions:

- A1. The given mesh is quadrilateral with a rectangle-shaped boundary;
- A2. Internal vertex is regular, with valence 4;
- A3. Mesh represents a single-valued surface $\mathcal{M}: \Omega \subset \prod \rightarrow \mathbb{R}$ with respect to a plane $\prod$.

Several techniques for extracting height maps are documented in the literature. A straightforward approach is presented in (Wang et al., 2003), which is designed specifically for modelling tree bark by extracting height maps from single photographs of the bark surface. Another more general approach consists of computing the height map as the normalised distance of surface points from the camera in a 3D scene (De Toledo et al., 2008). The authors Lai et al. (2005) proposed to measure the distance between the surface geometry and its corresponding base surface (macrostructure) by means of geometry images (Gu, Gortler & Hoppe et al., 2002).

To optimise the process and simplify the workflow, we created a tailored method for generating height maps from 3D surfaces representing fabric samples, specifically designed to support our texture extraction objective.

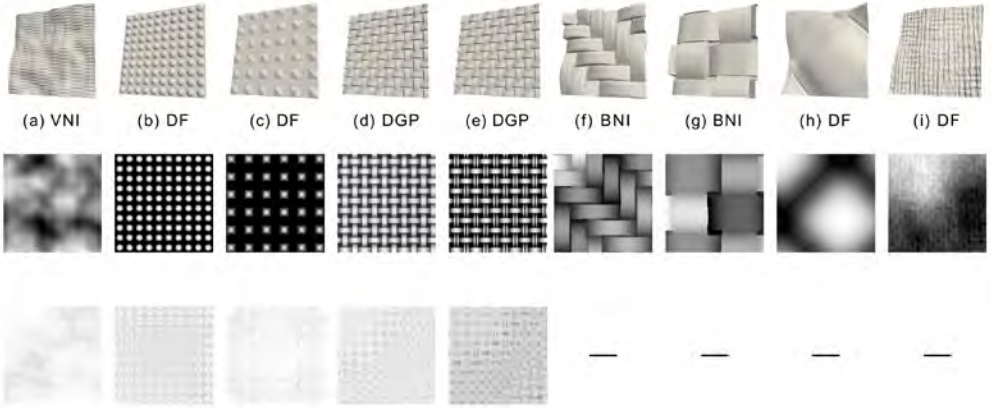
Under the assumptions $A1$, $A2$, $A3$, the height map is generated by measuring the distance of each mesh vertex from the plane $\prod$. The equation of the plane $\prod$ is obtained by applying the principal component analysis to the vertices of $\mathcal{M}$. Then the sought plane is spanned by the obtained two principal directions. The definition of the plane can introduce ambiguity, as distances can be calculated relative to any plane parallel to $\prod$. This ambiguity is solved by normalising the distances calculated between the plane and the mesh. By denoting with d_{max} and d_{min} the maximum and minimum orthogonal distances between the vertices $v_i \in \mathcal{M}$ and the plane $\prod$, the distances d_i are transformed into $\bar{h}_i \in [0,1]$ in the height map image $\mathbf{H}$ as

$$\bar{h}_i = \frac{d_i - d_{min}}{d_{max} - d_{min}} \quad (3.1)$$

Height maps are grayscale images stored with $b = 16$ up to $b = 64$ bits since 8 bits are usually not sufficient to represent the values $\bar{h}_i$. The conversion to the height map therefore involves the mapping values $\bar{h}_i$ by

$$h_i = \left\lfloor \bar{h}_i \cdot (2^b - 1) \right\rfloor \quad (3.2)$$

Figure 3 illustrates the height maps extracted from the best-performing reconstructed surfaces based on MSAE values.



3. The first row shows textile samples, followed by their extracted height maps in the second row. For textile samples with ground truth (a) – (e), the error images defined in (3.3) are shown in the third row.

The textile samples are displayed in the first row, with their corresponding extracted height maps presented in the second row.

Textile samples with available ground truth surfaces allowed for a quantitative assessment of the extracted height map. Given two images $\mathbf{I}_1$ and $\mathbf{I}_2 \in [0,1]$, the error image $\mathbf{E}$ is computed as follows:

$$\boldsymbol{E} = \log_{10} |\boldsymbol{I}_1 - \boldsymbol{I}_2| \quad (3.3)$$

Lastly, $\boldsymbol{E}$ is converted to a grayscale image. The error images are presented in the third row of figure 3, where black pixels highlight the maximum error areas.

4. Textile displacement mapping

The objective of the third phase of the proposed framework is to transfer the textile pattern onto a garment represented by a smooth surface. This process, known in computer graphics as *displacement mapping*, aims to perform a real modification of the object's geometry by adding new fine geometric details to the macrostructure of the garment.

The resulting new mesh with incorporated modified geometry allows for wide transferability and prototyping going further than mere visualisation, e.g. 3D printing, modelling, etc.

In fig. 4 we illustrate the two-stage displacement mapping setup: the texture domain parameterised in (s, t) (left) represents the height map domain; the parametric domain of the smooth surface $\mathcal{S}$ (center); and the 3D object space of $\mathcal{S}$ (right).

A necessary requirement for the displacement mapping is the UV parameterisation of the target mesh object $\mathcal{S}$. Moreover, for an optimal result, this parameterisation should be near isometric.

The proposed displacement procedure takes as input:

1. Target mesh $\mathcal{S}$ with possible isometric parameterisation.
2. Sample texture represented by its height map.
3. Physical dimensions of A_0 and its placement A_{uv} in the parametric domain (u, v).

The input requirement 3 indirectly allows us to identify the region of interest A_s on the smooth surface $\mathcal{S}$, where the fabric will be mapped.

The actual physical dimensions of the fabric sample A_0, see fig. 4 left, play a crucial role in achieving favourable results. By specifying the size of the sample and comparing it with the dimension of the region of interest in the mesh A_s, see fig. 4 right, the proposed adaptive displacement mapping procedure ensures the consistent preservation of proportions between the object and the fabric.

The best results are achieved when the texture's granularity and the mesh's vertex density are comparable. However, the number of texels in A_0 is, in general, different from the number of vertices in A_s, and we recognise the following two situations:

a) The number of texels is much less than the number of vertices.
b) The number of texels is much greater than the number of vertices.

For the case *a*), to adapt the texture to the target area on the mesh, we propose to simply interpolate the texel information, e.g. via nearest neighbours or linear interpolation. In case *b*), the situation presents more difficulties and affects the accuracy of the displacement mapping. It corresponds to having a low-poly mesh, which could prevent the reproducibility of all the detailed geometric features in the texture onto the few vertices of the surface. Four approaches can be applied to address this issue: *multum in parvo* (MIP) Mapping, Displaced Subdivision Surface, their combined approach, and Geometric Texture Transfer (GTT). MIP Mapping involves resizing the texture image into a MIP map pyramid, allowing displacement mapping to use the appropriate image level for the object's detail. The Displaced Subdivision Surface technique (Hoppe et al., 1994; Lee, Moreton & Hoppe, 2000; Niessner & Loop, 2013) subdivides the faces of the mesh representing the macrostructure to refine the mesh at the desired vertex density, aligning the mesh with the texture's granularity. The combined approach integrates both MIP Mapping and Subdivision Surface techniques for optimal results. Alternatively, Huska, Morigi & Recupero (2023) pro-

posed to replace the low-poly region with a dense enough patch containing the details, thus imposing only a subdivision of its boundary. To facilitate the detail transfer, the method relies on local geometric descriptors.

In this work we adopt a modified version of the MIP Mapping strategy used in computer graphics, to adjust the proportion issue in the displacement mapping approach.

4.1. Texel-vertex MIP mapping

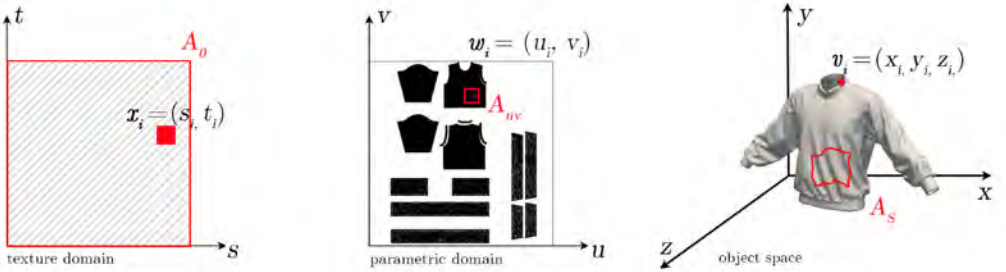
In this section, we describe the proposed strategy for adjusting the resolution of texels in the texture image with that of the vertices in the 3D mesh $\mathcal{S}$. This strategy is inspired by MIP mapping, which is a pre-computed texture scheme used in computer graphics that tries to solve the problem of texture map aliasing. Unlike the classical MIP mapping which is performed between an image and a rendering view plane, we need to map an image of the area A_0 to the covered surface area A_s, parameterised in A_{uv}. The proposed texel-vertex MIP mapping is developed in three successive steps:

1. MIP map texture pyramid construction.
   Starting from the original height map $\boldsymbol{I}_0$ with dimensions $h_0 \times w_0$ (in pixels), the MIP map texture pyramid is generated through successive resizing operations, reducing the number of pixels by half along each side. At level l of the MIP map, the image is defined as:

$$\boldsymbol{I}_l = \text{resize}\left(\boldsymbol{I}_{l-1}, \frac{h_{l-1}}{2}, \frac{w_{l-1}}{2}\right) \quad (4.1)$$

   where resize denotes the subsampling function used to resize the image $\boldsymbol{I}_{l-1}$ to dimensions $\left(\frac{h_{l-1}}{2}\right)\times\left(\frac{w_{l-1}}{2}\right)$. In fig. 5 we illustrate an example for $\boldsymbol{I}_l$, $l = 1, \ldots, 4$, four levels of the MIP map pyramid.

2. Computation of A_s and of its resolution.
   Given the physical dimension of the area A_0, we need to identify a surface patch $A_s \subset \mathcal{M}$ on the object such that



4. 2-stage mapping between the texture, parametric and object domain (color figure online).



5. Example of MIP map texture pyramid constructed for the height map image on the left at level $l = 0$. The image dimensions in pixels are reported in parentheses.

its area is comparable to A_0, i.e. $A_0 \simeq A_S$. The region A_S is achieved by applying a region-growing strategy. Starting from the first disk $\mathcal{N}_f(\mathbf{v}_i)$ of a vertex $\mathbf{v}_i \in \mathcal{M}$, which corresponds to a random point $\mathbf{w}_i$ in A_{uv}, the region expands by adding new faces belonging to the first disks of unlabelled outer vertices:

$$A_S = A_S \cup \mathcal{N}_f(\mathbf{v}_j), \qquad j \in \mathcal{N}(\mathbf{v}_i), \qquad \mathbf{v}_i \in A_S \quad (4.2)$$

Where $\mathcal{N}_f(\mathbf{v}_i)$ and $\mathcal{N}(\mathbf{v}_i)$ denote the first disk and the first ring of vertex $\mathbf{v}_i$, respectively.
The expansion of the region A_S terminates upon reaching the surface area of A_0. After obtaining A_S, its resolution is given by the number of vertices contained in A_S, i.e. $n_v = \#\{\mathbf{v}_i \mid \mathbf{v}_i \in A_S\}$.

3. Selection of the appropriate MIP map level.
The appropriate MIP map level l is then determined as follows:

$$\min_l \left| \frac{A_S}{n_v} - \frac{A_0}{h_l w_l} \right| \quad (4.3)$$

where $\frac{A_S}{n_v}$ represents the vertex average density of the region A_S in the object space and $\frac{A_0}{h_l w_l}$ corresponds to the pixel average density at each level l of the MIP map pyramid, see fig. 5.

4.2. Geometry displacement

Given a mesh $\mathcal{M}$ with UV parametrisation, which allows the association of each vertex $\mathbf{v}_i = (x_i, y_i, z_i)$ with a point $\mathbf{w} = (u_i, v_i)$ in the parametric domain, the displacement mapping moves each vertex $\mathbf{v}_i$ according to the displacement in the associated texture pixel (*texel*) $\mathbf{x}_i = (s_i, t_i)$. The coordinates (s_i, t_i) are derived from the parametric coordinates (u_i, v_i).

The proposed displacement mapping method allows for positioning texture by rotation and translation with respect to the

parametric domain, and it supports two tiling modes: simple repetition and clamp.

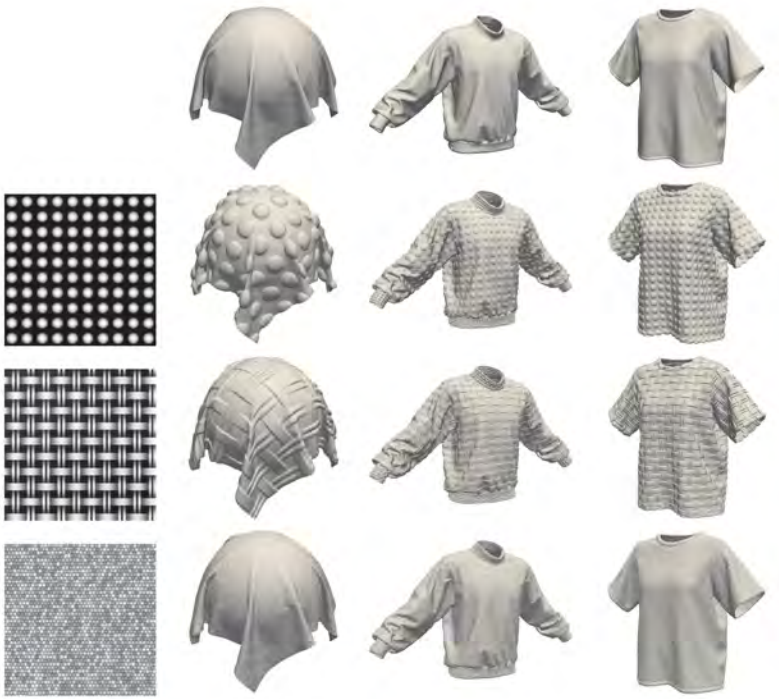
Given the texel size $m = \frac{c}{h}$ and the user-defined parameters for the displacement mapping application, including the translations $T_{\Delta s, \Delta t}$ in the parametric plane, and the rotation matrix R_{ϕ} with rotation angle ϕ, the vertex $\mathbf{v}_i$ can be mapped to texel space coordinates as follows:

$$(s_i, t_i) = \left\lfloor T_{\Delta s, \Delta t}\left(R_{\Phi}\left(\frac{(u_i, v_i)}{m \cdot \delta_{u,v}} \right) \right) \right\rfloor \quad (4.4)$$

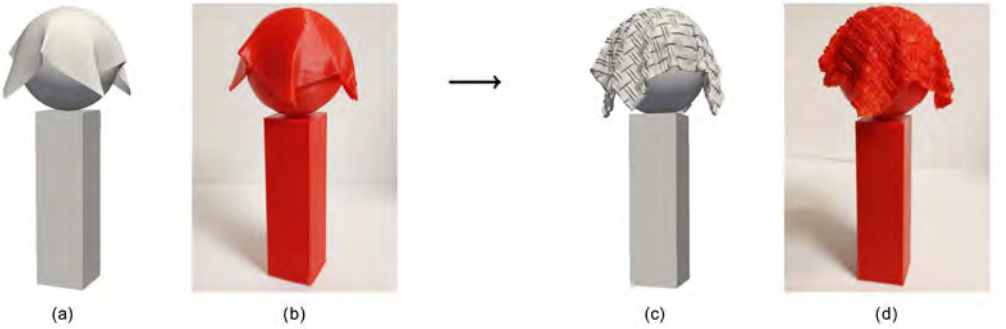
with $\delta_{u,v} := \sqrt{\frac{A_{uv}}{A_S}}$ the scaling factor related to the UV mapping. In order to apply the texture tiling with repetition, the texel coordinates associated with each vertex must lie within the texture domain $(s_i, t_i) \in [h, w] \times [h, w]$, achieved using the modulo operator: $s_i' = s_i \bmod h$, $t_i' = t_i \bmod w$. To avoid texture repetition, the coordinates (s_i, t_i) are compared to the image domain. Displacement is applied to the vertex $\mathbf{v}_i$ only if $(s_i, t_i) \in [h, w] \times [h, w]$; otherwise, the vertex remains unchanged.

4.3. Experimental results for stage (III)

The first example of displacement mapping, illustrated in fig. 1 (right), involves a square *cloth*, the smooth surface that needs to be textured, and draped over a sphere. This simple example, presenting a comparable texel-vertex density, did not require any MIP mapping procedure. To comprehensively analyse the robustness of the proposed MIP mapping approach, the displacement mapping procedure has been further applied to additional 3D models with non-isometric parameterisation, namely the *sweatshirt* and *t-shirt* models, see fig. 6 first row. The visual results of the displaced models using repetition tiling mode are presented in fig. 6. The displacement mapping appears visually truly accurate. However, since the *sweatshirt* and *t-shirt* models present a non-isometric parameterisation and complex topological features, the displaced meshes in the last two columns exhibit qualitative inferior results compared to the isometrically-parameterised *cloth*.



6. Displacement mapping applied to a selection of height maps (first column) on various 3D models with smooth surfaces (first row).



7. 3D printed model: (a) the 3D digital model of the base original textile and (b) its 3D print; (c) the 3D digital model of the displaced textile sample with geometric details and (d) its 3D print.

In a generic 3D modelling software, applying the displacement map to the base mesh will modify the vertex positions based on the values in the texture map, creating a more detailed digital surface model.

Then, it is possible to export the mesh as a file format suitable for 3D printing, such as STL or OBJ. In fig. 7 we illustrate the 3D printing results for the *cloth* model. A prototype of the displaced cloth was printed together with an accompanying pedestal (a sphere atop a cuboid) using the QIDI X-MAX2 3D printer. The pedestal and cloth were printed separately to facilitate the placement and removal of the cloth print on the sphere.

5. Conclusion

In this work, we analysed three important stages in the process of replicating a textile fabric sample to its virtual twin. First, various normal integration techniques were validated to produce a faithful 3D mesh reconstruction from a given normal map observation. The efficient BNI method proved superior performance in preserving discontinuities in the reconstructed mesh. However, also the VNI method provides good accuracy with competitive timing performance. The computation time of the VNI method can be further reduced by employing numerical solutions based on discrete cosine transform.

In the second stage, an ad hoc procedure was designed to generate height maps from quadrilateral meshes with rectangle-shaped boundaries. At this aim, the projection plane has been defined by the first two principal directions obtained by the principal component analysis of the vertices of the input mesh.

Finally, a new texel-vertex MIP mapping procedure was introduced to facilitate displacement mapping in the adaptive mapping of a high-definition height map onto the region of interest on smooth surfaces. This has made it possible to solve the problem of disparity in the density of vertices between texture and part of the mesh to which the texture is associated, allowing a pleasant result. A real change of the mesh geometry, which faithfully reproduces all the texture details, has an important impact on the PNRR project, both for further manipulations in VR/XR environments with haptic support and in the prototyping using 3D printing.

References

Apollonio et al., 2021
Apollonio, F. I., Foschi, R., Gaiani, M., & Garagnani, S. (2021). How to analyze, preserve, and communicate Leonardo's drawing? A solution to visualize in RTR fine art graphics established from "the best sense". *Journal on Computing and Cultural Heritage (JOCCH)*, *14*(3), 1–30.

Bi & Wang., 2010
Bi, Z., & Wang, L. (2010). Advances in 3D data acquisition and processing for industrial applications. *Robotics and Computer-Integrated Manufacturing*, *26*(5), 403–413. https://doi.org/10.1016/j.rcim.2010.03.003

Bourke & Green, 2016
Bourke, P., & Green, J. (2016). Keeping it real: Creating and acquiring assets for serious games. *The Computer Games Journal*, *5*(1-2), 7–22. https://doi.org/10.1007/s40869-016-0018-z

Cao et al., 2021
Cao, X., Shi, B., Okura, F., & Matsushita, Y. (2021). Normal integration via inverse plane fitting with minimum point-to-plane distance. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (pp. 2382–2391).

Cao et al., 2022
Cao, X., Santo, H., Shi, B., Okura, F., & Matsushita, Y. (2022). Bilateral normal integration. In *Proceedings of European Conference on Computer Vision (ECCV)* (pp. 552–567).

Cook, 1984
Cook, R. L. (1984). Shade trees. In *Proceedings of the 11th annual conference on Computer graphics and interactive techniques* (pp. 223–231).

Cook et al., 1987
Cook, R. L., Carpenter, L., & Catmull, E. (1987). The Reyes image rendering architecture. *ACM SIGGRAPH Computer Graphics*, *21*(4), 95–102. https://doi.org/10.1145/37402.37414

De Toledo et al., 2008
De Toledo, R., Wang, B., & Levy, B. (2008). Geometry textures and applications. *Computer Graphics Forum*, *27*(8), 2053–2065. https://doi.org/10.1109/SIBGRA.2007.4368171

Fantini, Gaiani & Garagnani, 2023
Fantini, F., Gaiani, M., & Garagnani, S. (2023). Knowledge and documentation of renaissance works of art: The replica of the "annunciation" by Beato Angelico. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-M-2-2023 (pp. 527–534). https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-527-2023

Gu, Gortler, & Hoppe, 2002
Gu, X., Gortler, S. J., & Hoppe, H. (2002). Geometry images. In *Proceedings of the 29th annual conference on computer graphics and interactive techniques* (pp. 355–361).

Harker & O'Leary, 2015
Harker, M., & O'Leary, P. (2015). Regularized reconstruction of a surface from its measured gradient field: Algorithms for spectral, tikhonov, constrained, and weighted regularization. *Journal of Mathematical Imaging and Vision*, *51*, 46–70. https://doi.org/10.48550/arXiv.1308.4292

Hoppe et al., 1994
Hoppe, H., DeRose, T., Duchamp, T., Halstead, M., Jin, H., McDonald, J., Schweitzer, J., & Stuetzle, W. (1994). Piecewise smooth surface reconstruction. In *Proceedings of the 21st annual conference on computer graphics and interactive techniques* (pp. 295–302).

Huska, Morigi & Recupero, 2023
Huska, M., Morigi, S., & Recupero, G. (2023). Geometric texture transfer via local geometric descriptors. *Applied Mathematics and Computation*, *451*, 1–20. https://doi.org/10.1016/j.amc.2023. 128031

Lai et al., 2005
Lai, Y.-K., Hu, S.-M., Gu, D., & Martin, R. R. (2005). Geometric texture synthesis and transfer via geometry images. In *Proceedings of the 2005 ACM symposium on solid and physical modeling* (pp. 15–26).

Lee, Moreton & Hoppe, 2000
Lee, A., Moreton, H., & Hoppe, H. (2000). Displaced subdivision surfaces. In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques* (pp. 85–94).

MICS, 2023
MICS. (2023). *MICS Made in Italy Circolare e Sostenibile*. https://www.mics.tech/

Niessner & Loop, 2013
Nießner, M., & Loop, C. (2013). Analytic displacement mapping using hardware tessellation. *ACM Transactions on Graphics (TOG)*, *32*(3), 1–9. https://doi.org/10.1145/2487228.2487234

Pavlidis et al., 2007
Pavlidis, G., Tsiafakis, D., Koutsoudis, A., Arnaoutoglou, F., Tsioukas, V., & Chamzas, C. (2007). Preservation of architectural heritage through 3d digitization. *International Journal of Architectural Computing*, *5*(2), 221–237. https://doi.org/10.1260/1478-0771.5.2.222

Ponchio et al., 2024
Ponchio, F., et al. (2024). *Relight webpage*. https://vcg.isti.cnr.it/vcgtools/relight

Quéau, Durou & Aujol, 2017
Quéau, Y., Durou, J.-D., & Aujol, J.-F. (2017). *Normal integration: A survey*. https://arxiv.org/abs/1709.05940

Quéau, Durou & Aujol, 2018
Quéau, Y., Durou, J.-D., & Aujol, J.-F. (2018). Variational methods for normal integration. *Journal of Mathematical Imaging and Vision*, *60*(4), 609–632. https://doi.org/10.1007/s10851-017-0777-6

Thali, Braun, & Dirnhofer, 2003
Thali, M. J., Braun, M., & Dirnhofer, R. (2003). Optical 3D surface digitizing

in forensic medicine: 3D documentation of skin and bone injuries. *Forensic science international*, *137*(2-3), 203–208. https://doi.org/10.1016/j.forsciint.2003.07.009

Wang et al., 2003
Wang, X., Wang, L., Liu, L., Hu, S., & Guo, B. (2003). Interactive modeling of tree bark. In *11th Pacific Conference on Computer Graphics and Applications, 2003. Proceedings* (pp. 83–90).

Xie et al., 2014
Xie, W., Zhang, Y., Wang, C. C., & Chung, R. C.-K. (2014). Surface-from-gradients: An approach based on discrete geometry processing. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (pp. 2195–2202).

Zannoni et al., 2024
Zannoni, M., Foschi, R., Pucci, D., & Saponelli R. (2024). An immersive haptic experimentation for dematerialized textile perception in collaborative design processes. *SCIRES-IT-SCIentific RESearch and Information Technology*, *14*(1), 129–146. https://doi.org/10.2423/i22394303v14n1p129

ARTIFICIAL INTELLIGENCE AND EXTENDED REALITY IN FASHION: CREATIVITY AND HERITAGE PRESERVATION IN THE 2D-3D TRANSITION

Pasquale Cascarano, Gustavo Marfia*, Irene Calvi*, Eleonora Stacchiotti**

1. Introduction

The fashion industry is currently undergoing a significant transformation, driven by the integration of advanced technologies such as Artificial Intelligence (AI) and Extended Reality (XR), which includes Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) (Loureiro, 2023). These technologies are reshaping the way fashion is created, experienced, and preserved. Traditional 2D processes are being replaced by immersive 3D environments, where designers and consumers can explore and interact with fashion in unprecedented ways (Arribas & Alfaro, 2018).

This paper examines three crucial aspects in this shift: enhancement of creativity, preservation of the heritage, and improvement of user engagement, through the application of AI and XR paradigms in the fashion field.

AI is increasingly becoming a powerful tool for enhancing creativity within the fashion design process. Using data-driven approaches, designers are now able to push the boundaries of innovation, developing new styles and accelerating the design-to-production cycle. In particular, Generative AI (GenAI) is transforming how fashion concepts are visualized and prototyped, allowing designers to explore multiple creative possibilities and refine their ideas rapidly (Loureiro, 2023; Vallasciani et al., 2024a).

On the other hand, XR technologies, including AR, VR, and MR, are revolutionizing the visualization and manipulation in the field of fashion (Loureiro, 2023). They allow designers and consumers to interact with 3D models of garments in immersive environments, making real-time adjustments and facilitating new retail experiences, such as virtual fashion shows and try-ons. For instance, these technologies are increasingly used in

**Department of the Arts, Alma Mater Studiorum - University of Bologna, Italy*

virtual fashion shows and retail environments, allowing brands to offer customers interactive and immersive shopping experiences. XR enables consumers to engage with fashion collections in ways that go beyond the limitations of physical spaces (Calvi, Stacchiotti & Cascarano, 2024; Hajahmadi, 2024).

In addition to enhancing consumer engagement, both AI and XR technologies significantly support storytelling within virtual environments (Hajahmadi, 2024). Brands are using these technologies to highlight their legacy, from virtual tours of iconic locations to digital reconstructions of historical garments to preserve fashion heritage. Fashion, with its deep cultural and historical significance, faces a unique challenge: maintaining its legacy while embracing the fast digital transformation. AI and XR offer powerful solutions to bridge this gap by digitizing and safeguarding important fashion artifacts, making them accessible to future generations in immersive and interactive ways. More in detail, AI-driven 3D reconstruction techniques have been used to digitally archive historical fashion garments (Garzarella, Cascarano & Stacchio, 2024). Through advanced methods images of costumes from various sources (newspapers, historical archives, etc.) can be transformed into detailed 3D models. These processes have been shown to not only preserve the aesthetic and functional aspects of these fragile garments but also enables users to explore them in dynamic virtual environments. These digital reconstructions allow for a 360-degree view of costumes in XR, making it possible to examine intricate design details and fabric textures that are often difficult to access in traditional settings.

This paper outlines how AI and XR technologies are not only driving creative innovation but are also playing a pivotal role in preserving fashion's cultural heritage and enhancing user engagement in the shift from 2D to 3D fashion design. By drawing on diverse studies (Calvi, Stacchiotti & Cascarano, 2024; Garzarella, Cascarano & Stacchio, 2024; Hajahmadi, 2024; Vallasciani et al., 2024a), this paper offers a comprehensive overview of how fashion is evolving in the digital age.

The paper is organized as follows. Section 2 explores the role of CreAIXR, a portable XR platform that uses AI and XR technologies to enable creatives, like designers and curators, to define and manipulate objects in immersive environments. Sec-

tion 3 highlights the impact of VR and AI on the fashion industry, focusing on how these technologies create immersive virtual retail spaces that merge heritage with modern e-commerce, offering personalized experiences and trend analysis. Section 4 discusses the role of AI and XR in preserving fashion heritage through 3D digital reconstruction techniques, offering new ways to explore cultural artifacts.

2. Fostering creativity with Generative AI in XR environments

Creativity is essential for cultivating innovative thinkers, but traditional methods often fail to meet individual needs, especially in fields like visual arts, where creativity can be hindered by abstract concepts (Beghetto, 2016). Creativity involves two key cognitive processes: divergent thinking (idea generation and flexibility) and convergent thinking (focused problem-solving) (Guilford, 1967). Novel technologies like XR and AI can enhance both processes by offering immersive, interactive environments that remove constraints and stimulate creativity (Pandey et al., 2015; Yang, 2018; Stacchio et al., 2024a; Stacchio et al., 2024b). To address these needs, in (Vallasciani et al., 2024a) the authors introduced CreAIXR, a platform merging generative AI and XR to enhance collaborative creativity. CreAIXR enables users to customize immersive environments, fostering both divergent and convergent thinking. In the fashion field, creativity is central to both design and curatorial processes. Fashion professionals, whether designers or exhibition curators, need tools that allow them to both explore new creative concepts (divergent thinking) and focus on the precise execution and display of these concepts (convergent thinking) (Guilford, 1967). CreAIXR facilitates this balance by immersing creatives in a fully customizable environment, where they can design virtual spaces, experiment with visual aesthetics, and receive AI-generated outputs that spark new ideas or refine existing ones.

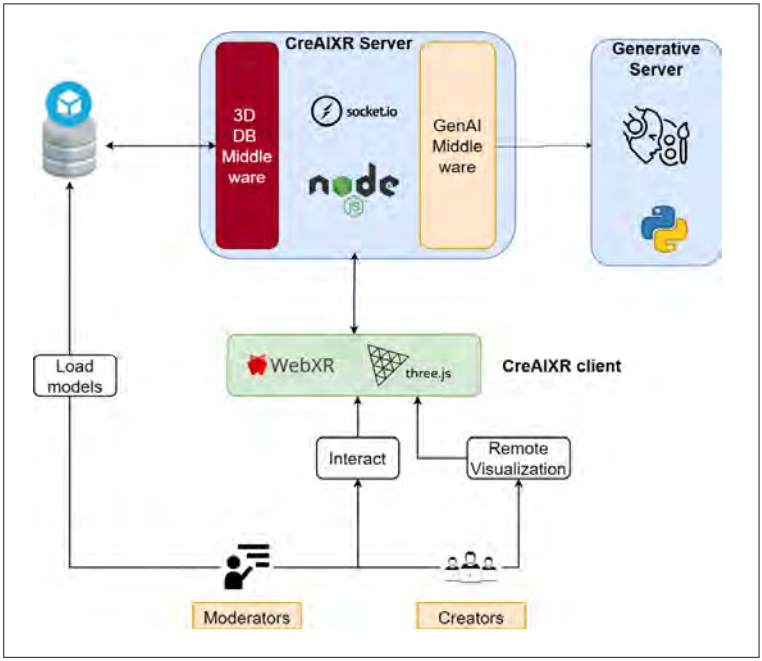
2.1. CreAIXR's system

CreAIXR is a portable XR platform designed to foster creativity through the integration of GenAI and immersive technologies. The system's architecture revolves around providing users with a

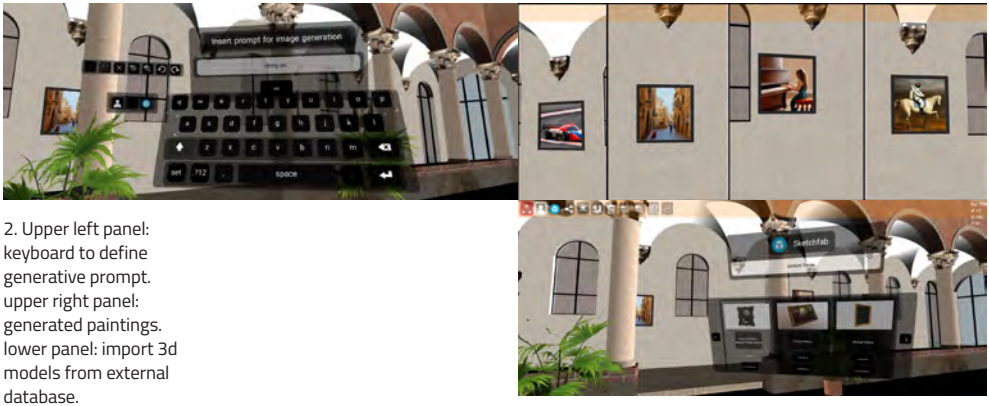
collaborative and customizable environment, combining XR paradigms with AI to allow real-time manipulation and creation of virtual objects. The core of the platform leverages web technologies, such as WebXR, Three.js, and Socket.io (Stacchio et al., 2024b), paired with generative AI models like Stable Diffusion (Rombach et al., 2022), allowing for the generation of 3D objects and immersive elements. Among the key features of CreAIXR we find its multiplayer client-server architecture, which enables real-time collaboration among users. These users can modify immersive environments by importing 3D objects from external databases (such as Sketchfab) (Stacchio et al., 2024b) or generating them on the spot using AI-based generative models (Vallasciani et al., 2024a). The platform also supports different levels of user privileges—moderators can manage sessions and other users, while creators can focus on generating and manipulating content. The system also allows for cross-reality interactions, supporting various devices like desktops, smartphones, and XR headsets. The system emphasizes data-driven architecture, with scene data and user profiles stored in JSON format, enabling efficient sharing, updating, and synchronization between users during sessions. This modular approach is particularly beneficial for scalability and adaptability in creative scenarios. An image of the architecture is drawn in figure 1.

Divergent thinking, characterized by the generation of multiple solutions and a flexible approach to problem-solving, is encouraged by the system's open-ended design, where users can explore various possibilities in terms of visual layouts, object manipulation, and scene customization. Conversely, convergent thinking, which focuses on narrowing down options to arrive at a singular solution, is fostered through the platform's AI-driven generative capabilities that help users refine and select the best creative ideas.

The system was assessed with students in Drama, Art, and Music Studies tasked with the creation of an art exhibition (fig. 2). The research findings show how CreAIXR enhances creativity and usability in art curatorship. Most participants had limited experience with XR and AI tools, making the results particularly insightful for newcomers. The post-experience data revealed that participants found CreAIXR easy to use and helpful in achieving their creative goals. The system was praised for



1. CreAIXR system architecture.
All images are reproduced in color in the online edition of the book.



2. Upper left panel: keyboard to define generative prompt. upper right panel: generated paintings. lower panel: import 3d models from external database.

simplifying the creation of virtual exhibitions, despite some concerns about network performance. One key strength of CreAIXR was its ability to foster collaboration, allowing users to work together in real-time, manipulate objects, and generate digital artworks. The generative AI module facilitated both divergent and convergent thinking, enabling participants to explore multiple creative possibilities and refine exhibition layouts. Participants found the platform effective for virtual museum creation, helping them understand spatial relationships and experiment with exhibition designs.

2.2. On the adoption of CreAIXR in the fashion field

The application of CreAIXR in the fashion field holds promise for fashion exhibition curators and designers. Through an immersive experience, curators can craft exhibitions in virtual environments, arranging garments, accessories, and other fashion elements in a way that reflects their aesthetic vision. This XR platform eliminates the constraints of physical spaces, allowing curators to experiment freely with layouts, lighting, and spatial arrangements, thus enhancing their ability to present fashion as both art and cultural artifact. Fashion designers, on the other hand, can leverage the platform's GenAI tools to create virtual fashion pieces, generate design inspirations, or visualize collections in a three-dimensional, immersive context. By using AI-generated elements, designers can accelerate their creative processes, exploring an array of styles, textures, and patterns that might not have been immediately accessible through traditional means. The generative aspect of the platform thus plays a vital role in breaking creative barriers and fostering original designs. In the specific use case of fashion curatorship, CreAIXR's collaborative nature also enables curators to collaborate with designers, artists, and other stakeholders in real-time, enhancing the overall creative process. The virtual exhibition environments that the system offers can be tailored to display collections in innovative ways, enhancing storytelling through visual immersion. The findings from experiments conducted with users in creative fields show that participants found the system easy to use, and the integration of AI tools significantly enhanced their creativity and productivity (Vallasciani et al., 2024a). Finally, CreAIXR can support both the ideation phase

(divergent thinking) and the execution phase (convergent thinking) of creativity within the fashion industry, making it an innovative tool for fashion exhibition curators and designers looking to push the boundaries of their creative capabilities.

3. Virtual retail environments enhanced by heritage elements and AI tools

In the rapidly evolving digital landscape, the convergence of heritage elements and AI tools within virtual retail environments is transforming the fashion industry (Hajahmadi, 2024; Kim & Forsythe, 2008; Moorhouse, Tom Dieck & Jung, 2018). This section examines how the integration of these two components not only enhances user engagement but also creates more immersive and meaningful brand experiences. Heritage elements serve as a bridge to a brand's history, while AI tools provide personalization and predictive capabilities, creating a constructive collaboration for the enhancement of fashion retail.

3.1. The role of heritage in virtual fashion spaces

Heritage plays a pivotal role in shaping the narrative and identity of fashion brands. By integrating historical and cultural elements, virtual retail environments offer consumers a deeper understanding of a brand's legacy. These heritage-driven narratives provide a sense of authenticity and emotional connection, which can foster greater consumer loyalty (Hrimes, 2023; Iannilli, 2014). In Hajahmadi (2024) the analysis of several case studies illustrates the widespread adoption of heritage elements in virtual retail spaces by famous luxury fashion brands. For example, the use of virtual exhibitions or immersive tours provides a multisensory experience that captures the essence of a brand's history, such as iconic locations, founders' personal stories, and the craftsmanship behind luxury items (Andò, Briatore & Denaro, 2023). These heritage elements often revolve around three macro-themes. First, the personal history of the founder or creative director is pivotal in building emotional connections with consumers. In fashion, shifts in creative leadership often mark the beginning of new stylistic phases for brands, with the founder's legacy serving as a crucial anchor for

storytelling. For example, Coco Chanel's legacy is tightly woven into the brand's identity, with her iconic salon and apartment at 31 Rue Cambon becoming synonymous with the Chanel aesthetic. Virtual spaces can simulate these historical locations, as seen in exhibitions that replicate the famous mirrored staircase of Chanel's atelier, offering consumers an interactive way to experience the brand's heritage. Second, specific physical spaces, such as the first atelier or other locations tied to a brand's development, act as cultural symbols within virtual spaces. These locations help to solidify the brand's identity while also serving as recognizable touchpoints for consumers. For instance, by recreating historically significant locations in a virtual environment, brands can allow users to explore their evolution in ways that are both informative and emotionally engaging.

Third, the detailed craftsmanship and artisanal knowledge that define luxury fashion are vital storytelling elements. Virtual environments allow brands to emphasize the meticulous techniques, materials, and cultural knowledge behind their products. By displaying these processes in a virtual space, brands can communicate the exclusivity and authenticity of their products, fostering a deeper connection with consumers who value tradition and craftsmanship.

3.2. AI Tools Enhancing the Virtual Experience

AI is increasingly becoming a key driver in fashion retail, primarily aiming to enhance customer satisfaction through personalization. AI-powered algorithms enable retailers to offer tailored fashion experiences by curating personalized recommendations based on individual tastes and preferences, boosting customer satisfaction and loyalty. These AI tools also assist designers in pushing creative boundaries, helping to generate unique pieces and enabling rapid prototyping and innovation (Yu, 2019). A particularly impactful AI application is avatar-based storytelling. Avatars serve as digital representations of users in virtual environments, facilitating interactive and communicative experiences. The use of avatars in VR allows for deeper exploration of identity and digital world engagement, providing a more relatable and personal interaction model between users and AI (Sibilla & Mancini, 2018). These AI-driven avatars create new possibilities for storytelling, making virtual narratives



3. Dolce & Gabbana virtual boutiques of Venice (upper half) and Rome (bottom half) venues displaying the brand's Italian heritage.

more immersive and personalized. AI's predictive analytics also play a crucial role in the fashion industry. By analysing large datasets, AI can accurately forecast trends, consumer preferences, and market shifts, helping brands stay ahead of trends while optimizing inventory management, reducing waste, and enhancing sustainability (Erhard & Bug, 2016). A study by Rovai, Pasquinelli & Teh (2023) further explored AI's integration into luxury retail atmospheres, highlighting its positive impact on the customer experience. The study also emphasized AI's effectiveness in enhancing omnichannel shopping journeys by seamlessly integrating online and in-store experiences. Luxury brands have been at the forefront of this technological revolution, particularly in merging AI and immersive experiences. Brands like Nike and those displayed at the VivaTech Summit in 2024, including LMVH, Sephora, and Dior, have leveraged AI to create innovative digital platforms and experiences. These AI tools, combined with immersive technologies, enhance customer engagement, creating personalized and interactive retail experiences that are redefining the luxury shopping landscape.

4. AI and XR for the preservation of fashion heritage

AI and XR have been proven effective for the preservation of cultural heritage, particularly in the fashion industry. These technologies address the challenges of safeguarding and presenting delicate, historical garments in a way that both respects their physical limitations and enhances their cultural significance. This section focuses on how AI and XR are applied in this context. Moreover, in the context of virtual environments security and privacy aspects are discussed.

4.1. Security and privacy aspects in collaborative virtual spaces

In fashion retail and collaborative design environments, ensuring the privacy and security of users is paramount, particularly when sensitive data are shared. In (Vallasciani et al., 2024b) the authors presents a comprehensive approach to handling security and privacy in collaborative virtual sessions, which can be applied in virtual fashion showrooms and design spaces. The approach is called SafeAR. For instance, when a designer is working

in a virtual fashion showroom, they may need to share confidential design concepts with a select group of collaborators. SafeAR allows the administrator to restrict access to specific virtual rooms or control interactions, ensuring that only authorized users can view sensitive content. This capability is particularly crucial in the fashion industry, where early access to unreleased designs could lead to intellectual property theft or leaks. The ability to dynamically manage permissions and protect shared content helps maintain the security of collaborative virtual fashion spaces, fostering trust and innovation within the industry.

4.2. A comparative analysis of 3D Reconstruction methods in fashion preservation

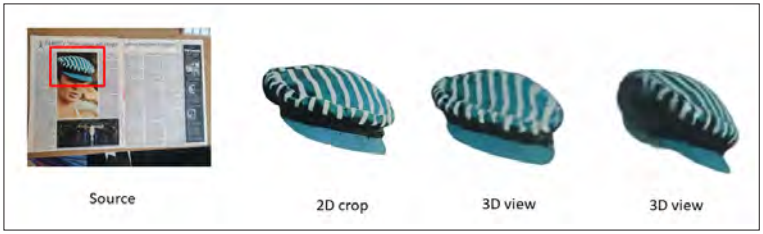
AI is playing an increasingly important role in preserving and enhancing fashion heritage, particularly through 3D reconstruction techniques. A comparative study of 3D reconstruction methods, including LiDAR, structured light scanning, and video-based techniques like Gaussian Splatting, highlights their applications in fashion heritage preservation. Each method offers unique strengths for various aspects of garment reconstruction. More in details:

- Structured light scanning through the Artec Eva scanner, is ideal for capturing fine details in garments with high precision. This method is particularly useful for documenting delicate fabrics and embellishments found in high-fashion pieces;
- LiDAR, often used with devices like the iPhone, provides a quick and accessible way to capture large garments or installations but may struggle with intricate details;
- Gaussian Splatting is a more recent technique that excels in creating realistic and photorealistic 3D reconstructions, even from low-quality images, making it a powerful tool for fashion heritage preservation.

These methods are crucial for digitizing fashion artifacts, making them available in virtual environments where they can be studied, displayed, and preserved without the risk of damage to the original physical pieces. An example of the application of these techniques on a particular garment is depicted in figure 4.



4. Two rendered 3D reconstruction' views (first and second rows) of the theatrical garment depicted in (e) with different approaches, namely (a) Artec Eva (b) LiDAR (c) Photogrammetry (d) Gaussian Splatting.



5. Views of the 3D model of a hat taken from a magazine (Paris, "Noureev Collection"/ Press/1972, Centre national de la danse).

Another compelling case study involves the preservation of Rudolf Nureyev's costumes using AI-driven techniques such as Gaussian Splatting (see fig. 5) (Garzarella, Cascarano & Stacchio, 2024). These technologies allow for the creation of highly detailed 3D models of historical garments from 2D images sampled from various sources (such as newspapers or images in foundation's archives). In this case the use of Gaussian Splatting techniques allows curators to create 360-degree views of intricate costumes, enabling users to interact with them in a virtual environment. This not only helps preserve the physical aspects of the garments but also ensures their legacy is accessible to future generations in digital form.

5. Conclusion

The integration of AI and XR technologies is transforming the fashion industry, enhancing creativity, heritage preservation, and user engagement. AI-driven generative models and immersive XR platforms enable designers and curators to explore and refine ideas in 3D environments, fostering innovation. These technologies also play a crucial role in preserving fashion heritage by digitizing fragile garments through advanced 3D reconstruction techniques, making them accessible to future generations. In virtual retail, AI and XR combine personalization with storytelling, creating immersive shopping experiences that strengthen brand-consumer connections. As fashion continues to evolve, AI and XR will remain key drivers of creativity, preservation, and engagement in the digital era.

References

Andò, Briatore & Denaro, 2023
Andò, R., Briatore, S., Denaro, G. (2023). Check for rethinking fashion storytelling through digital archives and immersive museum experiences. In *Fashion Communication in the Digital Age: Proceedings of the FACTUM 23 Conference* (pp. 279–289).

Arribas & Alfaro, 2018
Arribas, V., Alfaro, I. A. (2018). 3D technology in fashion: from concept to consumer. *Journal of Fashion Marketing and Management: An International Journal*, *22*(2), 240–251. https://doi.org/10.1108/JFMM-10-2017-0114

Beghetto, 2016
Beghetto, R. A. (2016). *Nurturing creativity in the classroom*. Cambridge University Press.

Calvi, Stacchiotti & Cascarano, 2024
Calvi, I., Stacchiotti, E., & Cascarano, P. (2024). Photogrammetry and 360° virtual tours: Differences, relevance, and future possibilities. In *AIVR 2024, The First International Conference on Artificial Intelligence and Immersive Virtual Reality* (pp. 7–12).

Chrimes & Boardman, 2023
Chrimes, C., & Boardman, R. (2023). The opportunities & challenges of the metaverse for fashion brands. In M. Brandstrup, L. P. Dana, D. Ryding, G. Vignali, & M. Caratù (Eds.), *The Garment Economy. Springer Texts in Business and Economics* (pp. 389–410), Springer.

Erhard & Bug, 2016
Erhard, J., & Bug, P. (2016). *Application of predictive analytics to sales forecasting in fashion business*. Reutlingen University.

Garzarella, Cascarano & Stacchio, 2024
Garzarella, S., Cascarano, P., & Stacchio, L. (2024). AI for enhancing and preserving dance cultural: A case study on Rudolf Nureyev's costumes. In *AIVR 2024, The First International Conference on Artificial Intelligence and Immersive Virtual Reality* (pp. 1–6).

Guilford, 1967
Guilford, J. P. (1967). Creativity: Yesterday, today and tomorrow. *The Journal of Creative Behavior*, *1*(1), 3–14. https://doi.org/10.1002/j.2162-6057.1967.tb00002.x

Hajahmadi et al., 2024
Hajahmadi, S., Calvi, I., Stacchiotti, E., Cascarano, P., & Marfia, G. (2024). Heritage elements and Artificial Intelligence as storytelling tools for virtual retail environments. *Digital Applications in Archaeology and Cultural Heritage*, *34*, 1–14. https://doi.org/10.1016/j.daach.2024.e00368

Iannilli, 2014
Iannilli, V. M. (2014). Retailing Made in Italy: An evolutionary reading towards emerging paradigms. *Fashion Practice*, *6*(2), 201–220. https://doi.org/10.2752/175693814X14035303880678

Kim & Forsythe, 2008
Kim, J., & Forsythe, S. (2008). Adoption of virtual try-on technology for online apparel shopping. *Journal of Interactive Marketing*, *22*(2), 45–59. https://doi.org/10.1002/dir.20113

Loureiro, 2023
Loureiro, S. M. (2023). *Artificial intelligence and extended reality in luxury fashion retail: Analysis and reflection*. Springer.

Moorhouse, Tom Dieck & Jung, 2018
Moorhouse, N., Tom Dieck, M. C., & Jung, T. (2018). Technological innovations transforming the consumer retail experience: A review of literature. In T.

Jung, M. C. Tom Dieck (Eds.), *Augmented Reality and Virtual Reality: Empowering Human, Place and Business*, Springer.

Pandey et al., 2015
Pandey, M., Luthra, V., Yammiyavar, P. G., & Anita, P. Y. (2015). Role of immersive virtual reality in fostering creativity among architecture students. In *Third International Conference on Design Creativity, Indian Institute of Science, Bangalore*.

Research, 2024
Research (March 20, 2024). *Case study: LVMH embraces AI*. https://aiexpert.network/case-study-lvmh-embraces-ai/.

Rombach et al., 2022
Rombach, R., Blattmann, A., Lorenz, D., Esser, P., & Ommer, B. (2022). High-resolution image synthesis with latent diffusion models. In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition* (pp. 10684–10695).

Rovai, Pasquinelli & Teh, 2023
Rovai, S., Pasquinelli, C., & Teh, C. (2023). AI in the luxury in-store atmospherics. *Symphonya*, *1*, 9–31. https://doi.org/10.4468/2023.01.02rovai.pasquinelli.teh

Sibilla & Mancini, 2018
Sibilla, F., Mancini, T. (2018). I am (not) my avatar: A review of the user-avatar relationships in Massively Multiplayer Online Worlds. *Cyberpsychology: Journal of Psychosocial Research on Cyberspace*, *12*(3). https://doi.org/10.5817/CP2018-3-4

Stacchio et al., 2024a
Stacchio, L., Garzarella, S., Cascarano, P., De Filippo, A., Cervellati, E., & Marfia, G. (2024). DanXe: An extended artificial intelligence framework to analyze and promote dance heritage. *Digital Applications in Archaeology and Cultural Heritage*, *33*, e00343. https://doi.org/10.1016/j.daach.2024.e00343

Stacchio et al., 2024b
Stacchio, L., Vallasciani, G., Augello, G., Carrador, S., Cascarano, P., & Marfia, G. (2024). WiXaRd: Towards a holistic distributed platform for multi-party and cross-reality WebXR experiences. In *2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* (pp. 264–272).

Vallasciani et al., 2024a
Vallasciani, G., Stacchio, L., Cascarano, P., & Marfia, G. (2024). CreAIXR: fostering creativity with generative AI. In *2024 IEEE International Conference on Metaverse Computing, Networking, and Applications (MetaCom)*.

Vallasciani et al., 2024b
Vallasciani, G., Schinoppi, A., Cascarano, P., & Marfia, G. (2024). Handling privacy and security aspects in a collaborative AR session. In *2024 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*.

Yang et al., 2018
Yang, X., Lin, L., Cheng, P. Y., Yang, X., Ren, Y., & Huang, Y. M. (2018). Examining creativity through a virtual reality support system. *Educational Technology Research and Development*, *66*(2), 1231–1254. https://doi.org/10.1007/s11423-018-9604-z

Yu et al., 2019
Yu, C., Hu, Y., Chen, Y., & Zeng, B. (2019). Personalized fashion design. In *Proceedings of the IEEE/CVF international conference on computer vision*.

GROUNDING FUTURE SCENARIOS OF TECHNOLOGY-ENHANCED FASHION HERITAGE: A PREPARATORY STUDY FOR THE STORYTELLING OF MADE IN ITALY

Irene Calvi, Eleonora Stacchiotti*, Pasquale Cascarano*, Gustavo Marfia**

1. Introduction

In the context of the project on the storytelling of Made in Italy Fashion in the Spoke 1 *Digital Advanced Design: technologies, processes, and tools* of the extended partnership MICS within the PNRR, this paper focuses on the definition of the potential application of digital twins in the design, production, and commercialization of fashion products. On a general level, the whole project departs from the object of the *digital twin*, which is used to draw new scenarios for the implementation of digital tools in the various steps of production and distribution of fashion items by Made in Italy brands. The authors will create a general framework to assess the project's progress while setting the theoretical foundations on which the expected result will be based.

In the first section, the authors will present the theoretical foundation from which they departed to understand the current situation at the intersection of Digital Heritage Marketing, Made in Italy Fashion Production and the employment of advanced technologies in the field of selling and exhibiting fashion. An insight into the state of the art of the development and the diffusion of digital twins will be offered. Digital twins are digital replicas of existing objects and that are nowadays used in several fields of industry and education.

The project involves the industrial partner AEFFE, a corporation that owns the right to design, produce and distribute the Made in Italy brands such as Moschino, Alberta Ferretti, Philosophy by Alberta Ferretti and Pollini. Therefore, theories, findings and their applications will be employed according to AEFFE's aims and requests. Nevertheless, while doing research and making prototypes for the industrial partner, the ambition of this research is to create tools which incorporate the cur-

**Department of the Arts, Alma Mater Studiorum - University of Bologna, Italy*

rent needs of the industry, keeping an eye open in the quest to understand the future trends of the intertwinement between fashion and immersive technology. Moreover, as fashion relates to questions of aesthetics and wider cultural trends, its dematerialization works as a case study to investigate current wider trends of virtualization and digitization of cultural artefacts, a topic which raises many questions such as the optimization of their automatized design through the integration of AIs into their production, their aesthetic quality, their readability for the user/spectator, who is now asked to perceive and appreciate luxury fashion—but also statues, paintings, buildings, *ephemera* and artefacts of all kinds—in new ways. This means that the study, design and investigation of the digitization of fashion entails the crossing of the traditional division of disciplines and calls for an interdisciplinary approach. This might be able to investigate the phenomenon more accurately.

2. State of the art: Setting in place a multidisciplinary approach

2.1. Heritage marketing: How to create cultural value for historical brands

Professionals and researchers have recently revalued the sources, traditions and knowledge transmitted from generation to generation in the firms of historical and long-lived brands (Riviezzo et al., 2014). This has sparked an interest in heritage marketing, which is now emerging as a set of practices that considers the use of historical cultural heritage to make the brand's identity and values conveyable and readable for the public. Italian enterprises with a long-lasting history have an extraordinary heritage composed of objects that are conserved in archives but do not have access to the proper means to transmit the brands' identity and values. In other words, long-lived firms have rich collections of historically relevant materials which are not turned into effective storytelling. Among the reasons, Riviezzo places the lack of systemic studies and comprehensive guides to inspire the brands' communication and strategy departments. As a matter of fact, the history of each brand is shareable and creates cultural value only as part of a well-structured narration of the traditional values and the

firm's culture. Therefore, Riviezzo compiled a list of categories which combine existing literature and practices on and about *heritage marketing*, as it follows:

Storytelling. This includes instruments and strategies where the power of storytelling involves all internal and external stakeholders. The brand's history can be conveyed through social media, corporate videos, advertising videos, and books. According to the main studies, storytelling is based on the history of brands, personalities that made the brands popular, the original knowledge, re-editions of iconic items, and the explorations of architectural buildings relevant to the brand's history.

Branding. Marketing activities related to the brand's identity built on emotional and symbolic elements are part of this. Among others, it is worth mentioning retro-branding initiatives, which revive iconic products reinforcing their evocative allure.

Organization units. These are the locations where the historical industrial memory can be valued and promoted. Being part of the urban setting, spaces such as corporate museums, archives and private foundations not only create value for the brand but enrich the cultural constellations of the surrounding context.

Public relations. Launch parties, merchandising activities and events promoting the iconic elements and moments of the history of the brand are included in this category.

According to these categories, our final project will eventually employ immersive technologies to add interaction to the experience of the customer. Augmented degrees of immersivity and interaction for the user of immersive technologies imply an enhanced level of interaction and psychological presence, which are believed to be more compelling for the user than a non-immersive experience.

2.2. The dynamicity of Made in Italy: A cornerstone of Italian fashion luxury

The concept of Made in Italy has evolved significantly since its inception, becoming synonymous with high-quality craftsmanship, luxury, and a rich cultural heritage (White, 2000; Belfanti, 2019; Savi, 2023). This narrative has deep historical roots, tracing back to post-World War II Italy when the country sought to rebuild its economy and establish a strong global presence in

fashion and design. Initially, Made in Italy was merely a label that denoted origin, however over the years it has transformed into a powerful symbol that evokes a sense of artistry and sophistication. Today, the narrative surrounding Made in Italy is not just about the products themselves but also encompasses the stories, traditions, and values embedded in the production processes. This broader perspective explains the ongoing interest in the topic and why it remains central to many interdisciplinary studies.

In the context of luxury fashion brands, transforming consumption into imagery and vice versa is critical. This dynamic underscores the importance of creating an aspirational lifestyle that resonates with consumers on an emotional level. For established brands, particularly those with a legacy to uphold, the challenge lies in maintaining their core identity while adapting to the evolving tastes and preferences of modern consumers. As creative directors change, the essence of the brand can shift dramatically, necessitating a careful balance between honouring the past and embracing contemporary trends. This scenario highlights the importance of specific elements in constructing a compelling imaginary that not only appeals to the consumer's aesthetic sensibilities but also reinforces the brand's heritage.

A pertinent case study in this discussion is that of Alberta Ferretti, a luxury brand renowned for its craftsmanship and attention to detail, founded and directed by Alberta Ferretti herself, who also started AEFFE S.P.A. A comprehensive analysis of luxury brands like Ferretti was conducted, focusing on the dissemination of brand values through promotional videos. This study, conducted by a group of researchers, including the authors, examined a curated selection of sixty promotional videos to investigate how the brand's legacy is articulated through various characteristics of visual narratives and marketing strategies, including narrative structure, protagonists, shooting style and editing, duration, and audio elements such as soundtracks and sound effects. The findings culminated in the creation of six tailored video pitches that encapsulate Ferretti's heritage, highlighting not only the artisanry inherent in their products but also the emotional resonance evoked by these narratives. By exploring the interplay between heritage and contempo-

rary marketing strategies, the study sheds light on how luxury brands can effectively communicate their legacy in a modern context.

2.3. Retail and exhibition spaces in fashion

The culture of fashion is displayed in a range of environments, from institutional settings to commercial spaces. Exploring the significance of these spaces, particularly virtual ones, unveils substantial opportunities to refine the presentation and understanding of fashion. Traditional museum exhibitions often treat fashion as a form of art or design, where objects take center stage as the narrative unfolds. In these exhibitions, curatorial choices frequently emphasize elements of brand heritage by incorporating historical or archival pieces, which enrich the storytelling aspect. In contrast, the retail environment operates as a dynamic platform for shaping and evolving brand identity through the spatial arrangement. With each store redesign or new location, the brand's aesthetic is reinterpreted, often favouring contemporary design over the historical elements that might otherwise reflect the brand's heritage. This evolving relationship between fashion and space becomes even more complex with the emergence of corporate museums, where business and cultural objectives intersect.

As highlighted by recent works, such as Matteo Augello's 2022 and Massimo Negri's 2024 publications, understanding corporate museums and their evolution is becoming increasingly important. Negri outlines fifteen foundational principles for corporate museums, applicable regardless of the specific collection. Among these are key objectives such as:

- Preserving a collection;
- Telling an entrepreneurial story;
- Highlighting and communicating the company's core values;
- Increasing the company's visibility;

Negri further categorizes corporate museums into distinct types, including "archive museums," "brand museums," and "theme park-entertainment center museums." These classifications underscore the variety of strategies companies employ to display their heritage and engage with the public.

Expanding on the discussion of spaces for fashion display, the rise of hybrid and virtual environments introduces compelling questions about how effectively they can convey brand identity. Virtual spaces, in particular, offer powerful opportunities for amplifying heritage through immersive, technology-driven experiences. These digital platforms can encapsulate a brand's essence, fostering deeper consumer engagement with its history and values. The potential for virtual spaces to not only display fashion but also strengthen connections to a brand's cultural significance is increasingly evident. As the fashion industry continues to evolve, integrating both physical and digital exhibition spaces will be pivotal in shaping how fashion is perceived and experienced. Recent prototyping has involved using A-Frame, an open-source web framework based on JavaScript, to build Virtual Reality (VR) experiences. Designing these open virtual spaces offers rich possibilities for aligning with a brand's identity. For instance, Moschino's evolving creative direction—from the founder Franco Moschino's original vision, through Jeremy Scott's bold American influence, to the upcoming work of a young Argentine designer—illustrates the ongoing research for balance of historical elements and the brand's core values. In summary, the convergence of corporate museums, retail environments, and virtual spaces marks a critical intersection in the display and communication of fashion. Each medium offers unique avenues for storytelling, brand identity, and consumer engagement, making them key to the future of fashion exhibitions.

2.4. Digital Twins: Translating and duplicating the real to create the digital

The concept of the Digital Twin (DT) originated from NASA's Apollo program in the 1970s when engineers explored the possibility of developing identical spacecraft on Earth to simulate and forecast the performance of those in space (Piascik et al., 2010). Although not an entirely developed digital twin system, the initiative underscored the value of creating physical replicas. In 2003, researcher Michael Grieves introduced the idea of a "Virtual Digital Expression Equivalent to Physical Product" as part of *Product Lifecycle Management* at the University of Michigan (Grieves, 2014). Initially called the *Mirrored Space Model* (Grieves, 2005) and later renamed the *Information Mirroring*

Model (Githens, 2007), this idea established the core elements of the DT, including the physical world, the virtual world, and their interface. Compared to the NASA Apollo program's twin concept, Grieves completed the shift from physical replicas to digital models. With the rise of Industry 4.0, DT have gained significant attention (Sharotry et al., 2020), and are defined as a technology that creates a digital replica of a physical entity using real-time data and models. This technology enhances automation and optimizes the management of physical systems. DT are widely used in various fields such as industry (Pires et al., 2019), healthcare (Opoku et al., 2021; Liu et al., 2019), and intelligent transportation (Rudskoy, Ilin, & Prokhorov, 2021; Sahal et al., 2021). With the rapid advancement of digital twins-related technologies like the Internet of Things (IoT), 5G/6G networks, and Artificial Intelligence (AI), researchers are now attempting to recreate DT in virtual space, adding to the physical objects the replica of biological systems. In the fashion industry, DTs are virtual replicas of physical fashion items, supply chains, and even individual customers and they represent a new frontier in fashion (Kuzmichev & Yan, 2022). These digital models enable designers to explore different design elements, materials, and styles without the need for physical prototypes. This approach not only streamlines the design process but also makes it more efficient and cost-effective, offering greater flexibility and control to fashion designers (Alam, Kabir, & Mirmohammad Sadeghi, 2023; Wagner, & Kabalska, 2023; Riedelsheimer, Dorfhuber, & Stark, 2020). DTs have the potential to enable large-scale personalization: through data and customer insights, fashion brands can create virtual avatars of their customers, offering tailored recommendations, style advice, and even virtual fitting experiences (Donmezer et al., 2023).

In recent years, innovative experiments in museological contexts have highlighted the potential of digital twins in fashion. For example, the 2013 exhibition "Charles James: Beyond Fashion" at the Metropolitan Museum of Art, showed a reconstructed 3D dress to display the intricate layering and diverse materials through engaging videos. Similarly, the 2023 exhibition at the Museum für Gestaltung in Zürich, titled "Balenciaga Reconstructed," combined a video illustrating the dress's pat-

terns with a physical garment on display and a digital twin that mirrored the movements of a catwalk. Furthermore, in spring 2024 the collaboration between d_archive and MoMu, the fashion museum in Antwerp, created a 3D replica of a 115-year-old linen riding costume by the Berlin tailor Hermann Hofmann from the MoMu Collection, bringing it to life in a manner that historical garments alone could not achieve.

3. First insights and experiments

3.1. The use of immersive technologies for the communication of fashion: A benchmark analysis

The understanding of the state of the art of use of digital twin and immersive technologies in the field of Luxury Fashion was fundamental as an initial step towards the creation of an immersive environment for Fashion garments' exhibition and sale. Therefore, as a team, we made a collaborative benchmark analysis of virtual tours available online. The sample has specific criteria: virtual environments available on mono-brand and multi-brand e-commerce websites, accessible without VR headsets and featuring fashion clothing, accessories, and makeup items in the Luxury market fragment. We identified forty significant cases meeting these criteria and focused on recurring elements through a systematic evaluation based on precise analytical points. Firstly, we analysed the aim of each experience, distinguishing between virtual environments integrating elements of brand cultural heritage and those designed exclusively for retail purposes. It is relevant to notice that many of them integrate gaming elements within the experience.

Elements considered indicative of brand heritage, based on Riviezzo (Riviezzo et al., 2016), include the presence of the founder or key figures, references to traditional manufacturing techniques, re-editions of iconic garments, and exploration of architecturally significant brand-related spaces. Secondly, we examined the technology used to create the experiences, categorizing them into 360° pictures, photogrammetry, and computer-generated environments. These techniques offer varying degrees of interaction and immersion, affecting how users

navigate and interact with the virtual environment. Interaction possibilities were classified as "Anchors" (navigation through buttons) and "Free Movement" (unrestricted roaming). User interaction with sale items was categorized as "Clicking" (opening e-commerce tabs within the virtual world) and "3D Objects" (interacting with items as 3D meshes).

Among the results, it is worth mentioning that virtual tours:

- Are realised through collaborations. In fact, they play a crucial role in expanding a brand's audience and enriching its offering. Partnering with established or emerging brands, multi-brand stores, or design studios allows for a combination of different skills and the creation of synergies that result in new experiences;
- Are often published for seasonal marketing events, such as collection launches, anniversaries, holidays, or major commercial events like sales and Black Friday;
- Are used as key strategies to enhance the brand heritage marketing through storytelling that highlights the brand's history, the figures who contributed to its success, traditional artisanry techniques, the reissue of iconic products and the exploration of architectural spaces representative of the brand;
- Are generated through a diversification of the digital representation of products, like photogrammetry and 3D design;
- Embed social media such as videocalls, likes, live-streams on Instagram for a real-time interaction.

In addition, among the strengths of the design of virtual tours, we noticed that it creates a more engaging and customizable shopping experience, increases accessibility to certain products, and increases the visibility of the brand's identity and its history. However, virtual tours require high maintenance costs and are not so sustainable, because of the obsolescence of the virtual tours. This is because every three months a brand should take the 360° pictures again according to the AF and SS seasons renewal. Moreover, most virtual tours had limited visibility on the brand's official website.

3.2. Two studies for a prototype experience: Visiting an immersive virtual exhibition and watching a dancer wearing an iconic garment in a historically relevant location

In our pursuit of crafting a compelling experience that enhances the brand's heritage marketing narrative, we developed two pilot projects exploring the potential for users to establish a connection with a digital twin, representing a digital replica of an existing item, whether through 3D design or appearance in a 360-degree video. The two projects were rooted in the concept of crafting an exclusive and immersive experience, aimed at democratizing access to rare and coveted items within the fashion realm. By making these items accessible and available to a wider audience, the projects seek to cultivate a sense of personal connection between consumers and the products they admire, while simultaneously fostering a vibrant community around the brand. In contemporary fashion marketing, the employment of brand ambassadors has become a prevalent strategy for launching and promoting new collections. Research has shown that brand ambassadors play a pivotal role in building consumer trust, which is widely regarded as a fundamental factor influencing purchasing decisions (Suleman et al., 2023). This phenomenon is particularly significant in today's digital age, where social media platforms serve as central hubs for fashion discourse and engagement (Chu, & Seock, 2020).

A preliminary experiment was conducted as part of the international summer school organized by Jagiellonian University in Kraków, aimed at investigating the role of interactive Virtual Reality (VR) experiences in the knowledge acquisition processes of museum visitors. The narrative framework of the study was inspired by the interaction between a virtual visitor and a museum guide, wherein each subsequent step of the experience was contingent upon the user's selected responses. This design sought to cultivate curiosity rather than discourage engagement; upon achieving a specified level of optimal interaction, participants were granted access to an exclusive collection piece not available for public viewing. The study focused on two principal aspects: first, the effects of user engagement and the methodologies employed to enhance it; and second, the implementation of the experience itself, which integrated a 3D replica that users could enlarge, rotate, and examine from multiple

perspectives. This dual focus aimed to elucidate the potential of VR technology to enrich the museum experience and facilitate deeper learning with the exhibited material.

A second low-cost prototype was designed to support preliminary experiments, focusing on creating an immersive, one-to-one experience. In this setup, a dancer or performer wears an iconic garment from a luxury brand and moves elegantly around a stationary camera, which represents the viewer's perspective. The prototype deliberately limits direct interaction and verbal communication between the performer and observer, emphasizing a deep connection between the viewer and the garment. By minimizing the observer's interaction with the human actor, the goal was to highlight the potential for an emotional bond with the garment itself. A short 360° video capturing this immersive encounter will be shown to a test group to evaluate its practicality and impact. To further explore the relationship between physical and virtual reality, the prototype will also be tested in the same environment where the 360° video was filmed. This will provide insights into how users perceive and interact with a virtual representation of a real space, offering guidance for future iterations. By blending elements of experiential marketing, immersive technology, and brand storytelling, this project aims to introduce innovative ways for fashion brands to engage with consumers. Through experimentation and refinement, the goal is to uncover new strategies for creating deeper, more meaningful connections between brands and their audiences.

4. Conclusion

In this paper we explored what has already been done and the next possibilities created using immersive technologies for the creation and the communication of cultural heritage for Made in Italy's brands. With this aim, the authors have done a literature review, offerend insights from the initial benchmark analysis and set the ground for the next steps of the project *Digital Advanced Design: technologies, processes, and tools*, which will be focused on the development of prototypes based on research findings, on both a national and international level, and current trends.

Acknowledgement

This paper was conceived by both authors in its entirety. Specifically, Irene Calvi is responsible for paragraphs 2.2., 2.3, and for the last lines of paragraph 2.4. Eleonora Stacchiotti is responsible for sections 1, 3, 4 and for paragraph 2.1 and the first part of paragraph 2.4.

References

Alam, Kabir, & Mirmohammad Sadeghi, 2023
Alam, M. D., Kabir, G., & Mirmohammad Sadeghi, S. (2023). A digital twin framework development for apparel manufacturing industry. *Decision Analytics Journal*, *7*(6), 100252. https://doi.org/10.1016/j.dajour.2023.100252

Augello, 2022
Augello, M. (2022). *Curating Italian fashion: Heritage, industry, institutions*. Bloomsbury Publishing.

Belfanti, 2019
Belfanti, C. (2019). *Storia culturale del Made in Italy*. Il Mulino.

Chu & Seock, 2020
Chu, S. C., & Seock, Y. K. (2020). The power of social media in fashion advertising. *Journal of Interactive Advertising*, *20*(2), 93–94. https://doi.org/10.1080/15252019.2020.1802955

Croatti et al., 2020
Croatti, A., Gabellini, M., Montagna, S., & Ricci, A. (2020). On the integration of agents and Digital Twins in healthcare. *Journal of Medical Systems*, *44*(9), 1–8. https://doi.org/10.1007/s10916-020-01623-5

Donmezer et al., 2023
Donmezer, S., Demircioglu, P., Bogrekci, I., Bas, G., & Durakbasa, M. N. (2023). Revolutionizing the Garment Industry 5.0: Embracing closed-loop design, e-libraries, and digital twins. *Sustainability*, *15*(22), 15839. https://doi.org/10.3390/su152215839

Githens, 2007
Githens, G. (2007). Product lifecycle management: Driving the next generation of lean thinking by Michael Grieves. *Journal of Product Innovation Management*, *24*(3), 278–280.

Grieves, 2005
Grieves, M. W. (2005). Product lifecycle management: The new paradigm for enterprises. *International Journal of Product Development*, *2*(1-2), 71–84. https://doi.org/10.1504/IJPD.2005.006669

Grieves, 2014
Grieves, M. (2014). Digital twin: Manufacturing excellence through virtual factory replication. *White Paper*, *1*(2014), 1–7. https://doi.org/10.5281/zenodo.1493930

Kuzmichev & Yan, 2022
Kuzmichev, V., & Yan, J. (2022). The application of digital twins in the field of fashion. In *Digital Twins: Basics and Applications* (pp. 45–57). Springer.

Liu et al., 2019
Liu, Y., Zhang, L., Yang, Y., Zhou, L., Ren, L., Wang, F., Liu, R., Pang, Z., & Deen, M. J. (2019). A novel cloud-based framework for the elderly healthcare services using digital twin. *IEEE Access*, 7, 49088–49101. https://doi.org/10.1109/ACCESS.2019.2909828

Opoku et al., 2021
Opoku, D. G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*, *40*(3), 102726. https://doi.org/10.1016/j.jobe.2021.102726

Piascik et al., 2010
Piascik, R., Vickers, J., Lowry, D., Scotti, S., Stewart, J., & Calomino, A. (2010). *Technology area 12: Materials, structures, mechanical systems, and manufacturing road map* (pp. 15–88). NASA Office of Chief Technologist.

Pires et al., 2019
Pires, F., Cachada, A., Barbosa, J., Moreira, A. P., & Leitão, P. (2019). Digital twin in Industry 4.0: Technologies, applications and challenges. In *2019 IEEE 17th International Conference on Industrial Informatics (INDIN)* (Vol. 1, pp. 721–726).

Riedelsheimer, Dorfhuber & Stark, 2020
Riedelsheimer, T., Dorfhuber, L., & Stark, R. (2020). User-centered development of a digital twin concept with focus on sustainability in the clothing industry. *Procedia CIRP*, *90*, 660–665.

Riviezzo et al., 2014
Riviezzo, A., Garofano, A., Marino, V., Napolitano, M. R. (2014). "C'era una volta…". Racconti d'impresa storiche della manifattura campana. *Sinergie*, *33*(98), 81–103. https://doi.org/10.7433/s98.2015.07

Riviezzo et al., 2016
Riviezzo, A., Garofano, A., & Napolitano, M. R. (2016). "Il tempo è lo specchio dell'eternità". Strategie e strumenti di heritage marketing nelle imprese longeve italiane. *Il capitale culturale. Studies on the Value of Cultural Heritage*, *13*, 497–523.

Rudskoy, Ilin & Prokhorov, 2021
Rudskoy, A., Ilin, I., & Prokhorov, A. (2021). Digital twins in the intelligent transport systems. *Transportation Research Procedia*, *54*, 927–935. https://doi.org/10.1016/j.trpro.2021.02.152

Sahal et al., 2021
Sahal, R., Alsamhi, S. H., Brown, K. N., O'Shea, D., McCarthy, C., & Guizani, M. (2021). Blockchain-empowered digital twins collaboration: Smart transportation use case. *Machines*, *9*(9), 193. https://doi.org/10.3390/machines9090193

Savi, 2023
Savi, L. (2023). *A New history of "Made in Italy". Fashion and textiles in post-war Italy*. Bloomsbury Publishing.

Sharotry et al., 2020
Sharotry, A., Jimenez, J. A., Wierschem, D., Mediavilla, F. A. M., Koldenhoven, R. M., Valles, D., Koutitas, G., & Aslan, S. (2020). A digital twin framework for real-time analysis and feedback of repetitive work in the manual material handling industry. In *2020 Winter Simulation Conference (WSC)* (pp. 2637–2648).

Suleman et al., 2023
Suleman, D., Suyoto, Y., Sjarief, R., Sabil, S., Marwansyah, S., Adawia, P., & Puspasari, A. (2023). The effects of brand ambassador and trust on purchase decisions through social media. *International Journal of Data and Network Science*, 7(1), 433–438.

Wagner & Kabalska, 2023
Wagner, R., & Kabalska, A. (2023). Sustainable value in the fashion industry: A case study of value construction/destruction using digital twins. *Sustainable Development*, *31*(3), 1652–1667. https://doi.org/https://doi.org/10.1002/sd.2474

White, 2000
White, N. (2000). *Reconstructing Italian fashion: America and the development of the Italian fashion Industry*. Berg Publishers.

DIGITAL DESIGN
FOR KNOWLEDGE SHARING

DIGITAL DESIGN FOR KNOWLEDGE SHARING

This cluster is articulated through projects 1.9 *SFIDA. Strategic Foresight for Innovation Design Augmentation*, 1.1 *FuturE-Pack. Digital Advanced Design for the Enhancement of Packaging as a Broadcaster in the Made in Italy Supply Chain*, 1.5 *Cross-sectoral Platform for Sustainable and Circular Textile*, and 1.7 *From Waste to Manufacturing: Digital Tools to Establish Virtuous Cycles*.

Project 1.9 is explored from three perspectives. The paper "Human and Artificial Elements in Foresight: Cyber-Creativity at the Service of Sustainable Futures" presents the development of a customized GPT model, attentive to cognitive and creative aspects, to support designers in integrating circularity and sustainability requirements into design processes. The paper "From Individual to Organizational Brain" introduces the Foresight Cognition Development Model, a framework that enhances strategic foresight in SMEs through the combination of cognitive training, mindfulness and organizational innovation. Finally, "Sustainability Transitions and Back-Casting for the Italian Fashion Industries" proposes a systemic foresight and strategic back-casting approach applied to the sustainable transitions of Italian fashion companies.

The FuturE-Pack project (1.1) is treated from two perspectives. The paper "Toward a Taxonomy of Smart Solutions for Advanced Packaging Design" elaborates a taxonomy of smart solutions for advanced packaging, while "Life Cycle Sustainability Assessment in Advanced Packaging Design" delves into the LCSA methodology and proposes a conceptual grid to assess the environmental impact of products.

With the contribution "Digital Waste Passport. Design a Cross-Sectorial Platform of Services to Facilitate Textile SMEs of Made in Italy in Achieving Traceability and Circularity," project 1.5 presents the development of a digital platform to support eco-design in the textile sector, based on the integration of digital tools already in use in the Made in Italy supply chain.

Finally, project 1.7 is illustrated by contribution "Processes for managing and designing circularity in the Italian furniture industry. Current practices and future strategies for tools of interconnectivity," which analyzes the use of digital tools for the design and management of circular materials, fostering interaction between designers, manufacturers and waste managers in the furniture sector.

HUMAN AND ARTIFICIAL ELEMENTS IN FORESIGHT: CYBER-CREATIVITY AT THE SERVICE OF SUSTAINABLE FUTURES

Ilaria Rinaldi, Irene Coletto*, Angela Faiella*, Stefano Rini*, Giulia Maria Vavassori*, Giovanni Emanuele Corazza**

1. Introduction

This contribution is the result of an interdisciplinary effort that spans over the disciplines of futures studies, cognitive psychology, creativity studies, and Generative Artificial Intelligence (Gen-AI), in order to provide essential epistemological support to designers in various fields, with particular attention to circular and sustainable design. We review the origins of futures studies and the wide set of methodologies that have been developed in the practice of strategic foresight. One of our main arguments is that great benefits can be obtained if this literacy in futures is complemented and augmented by intertwining with three other disciplines: psychology, creativity, and AI. In fact, knowing the cognitive and emotional correlates that are activated in a future thinking exercise can be instrumental in enhancing its effectiveness in the field. Exploiting creativity can aid the futurist to avoid "thinking in the box" traps, for example enhancing the surprise factors allowed by the use of wild cards and black swans. Also, Gen-AI tools hold the promise to significantly increase human productivity, and we report on the development of a cognitive-aware and creative custom GPT that can be used as a helper for designers in accounting for circularity and sustainability requirements in their work.

2. Historical evolution of Future Studies

Futures Studies, as a systematic exploration of future possibilities, has a rich historical evolution that has developed significantly over the past century. The journey began with H.G. Wells in the early 20th century. His *The Discovery of the Future*, (Wells, 1902) is considered a pioneering effort in scientific thinking about the future.

**DEI Department, Marconi Institute for Creativity, Alma Mater Studiorum - University of Bologna, Italy*

The mid-20th century marked a pivotal period for Futures Studies. RAND—a research organization known for its contributions to strategic planning—played a crucial role in formalizing the methodologies within the field (Hines, 2020). Kahn's seminal work, *On Thermonuclear War* (Kahn, 1960), introduced the concept of scenario planning, which became a cornerstone of Strategic Foresight. This method allowed for the exploration of multiple future possibilities, especially in the context of nuclear strategy during the Cold War.

The field began to embrace a more interdisciplinary approach, aligning with the philosophies of Karl Popper who emphasizing the importance of falsifiability in scientific and future-oriented predictions, called for rigor and encouraged collaborations across various disciplines, including sociology, economics, and engineering (Popper, 1957).

The 1970s brought a significant application of Futures Studies methodologies to the business world. Pierre Wack, working for Royal Dutch Shell, utilized scenario planning to navigate the uncertainties of the global oil market (Wack, 1985). Shell's ability to adapt during the 1973 oil crisis demonstrated the practical value of these methods in real-world situations.

The late 20th century saw further diversification and sophistication in Futures Studies. The advent of systems dynamics, particularly highlighted by Donella Meadows and her co-authors in *The Limits to Growth* (Meadows et al., 1972), provided new tools for understanding complex, interconnected systems. This approach allowed for the examination of long-term global trends and their potential impacts. Similarly, John Naisbitt's *Megatrends* (Naisbitt, 1982) popularized the concept of identifying and analyzing large-scale trends to predict future societal shifts.

The *Three Horizons Framework* (Sharpe, 1996) further refined strategic foresight by offering a structured approach to managing transitions from the present to desired future states. This framework helped organizations balance immediate needs with long-term vision, fostering a proactive rather than reactive stance towards future changes.

As the 21st century unfolded, the field continued to evolve, incorporating new technologies and methodologies. The rapid pace of technological advancement, globalization, and the increasing complexity of global systems necessitated more adap-

tive and inclusive approaches. Scholars like Riel Miller and Roberto Poli advocated for embracing complexity and uncertainty, promoting participatory methods and a holistic perspective on futures thinking (Miller, 2007; Poli, 2015).

Today, the evolution of Futures Studies continues, with a growing emphasis on integrating creativity and technological tools such as artificial intelligence (Corazza, 2017; 2024). The combination of human creativity and AI's analytical capabilities promises to enhance the robustness and depth of future projections, preparing organizations and societies to navigate an increasingly uncertain world.

3. Foresight methodologies

In foresight, navigating the complexities of an uncertain future involves a structured process composed of four key phases: Setting, Documentation, Visualization, and Application. These phases provide a systematic approach to transforming uncertainty into actionable insights. The *Setting phase* is foundational, where the foresight team defines the purpose, focus, methodologies, and timeframe for the exercise. Selecting the appropriate timeframe is crucial, akin to choosing the focal length of a camera lens—it shapes the clarity and relevance of the insights. For instance, a shorter timeframe might be suitable for Trend and Megatrend Analysis, while longer timeframes could align with methods like Delphi or Three Horizons Analysis, which explore deeper, long-term shifts. Choosing the right timeframe ensures that foresight efforts remain precise, relevant, and aligned with the organization's strategic goals, while also optimizing resource allocation.

The *Documentation phase* involves rigorous research and the creation of supporting materials. Here, methods like Environmental Analysis and Stakeholder Analysis are critical for understanding the current context and identifying key influences. Additionally, Weak Signals Analysis might be used to detect early signs of emerging trends, providing a broader view of potential future developments. This phase ensures that the foresight process is grounded in robust data and a comprehensive understanding of the factors that will shape the future.

In the *Visualization phase*, creative and analytical techniques

converge to explore future scenarios. Scenario Planning and Backcasting are central methods in this phase, allowing practitioners to map out different potential futures and then work backward to identify the steps needed to achieve or avoid them. Morphological Analysis can also be applied to systematically explore the relationships between different variables, creating a multi-dimensional view of possible outcomes. These methods enable the development of detailed, plausible scenarios that guide strategic decision-making.

Finally, the *Application phase* translates the insights gained into actionable strategies. This phase often involves the use of tools like Roadmapping, which aligns future goals with organizational actions, and Timelines, which helps track progress and anticipate critical junctures. Developing dashboards or visual tools to monitor key indicators ensures that the organization remains agile and prepared for future developments.

4. Psychological correlates to thinking about the future

Futures studies methodologies are applied in different disciplines, but the results are not always as expected. Methodologies often do not consider the cognitive correlates of future thinking (Faiella & Corazza, 2025). On the other hand, although there are many studies on psychological correlates, most of them focus on the short-term future of the individual. Few studies focus on the future of the community (Szpunar et al., 2014) and on the long-term future.

These differences indicate diverse approaches and interests in psychology versus foresight in the subject of futures, but at the same time, in both cases, a great interest in a scientific approach to the study of the future, the possibilities we might encounter, and the decision-making.

An interdisciplinary approach would fill the gaps and provide new insights into the knowledge of the collective long-term future. Collaboration between disciplines could begin by analyzing the cognitive correlates of futures thinking that have already been studied in psychology. Psychologists have investigated the elements that can influence or transform future thinking, such as memory (Schacter et al., 2012), biases and

heuristics (Salgado & Berntsen, 2020), motivation (Karniol & Ross, 1996), and emotions (Gilbert & Wilson, 2007). Whether memory and future thinking are the same thing is still debated, as there are similarities and differences at the neural and behavioral levels. For example, similar cognitive substrates are involved (Schacter et al., 2012), but the hippocampal responses are different (Weiler et al., 2010). At the behavioral level, we "mentally travel in time" between the past and the future (Suddendorf & Corballis, 1997), but we think about the future more often than the past (Schacter et al., 2012), even as children, around 4/5 years (Burns et al., 2019).

What is certain is that we cannot predict exactly what will happen, in part because we are never fully rational. We use mental shortcuts (heuristics) that create cognitive biases and many of these biases are related to thinking about the future, such as the optimistic bias, which leads us to mistakenly view the future as more positive than the past (Salgado & Berntsen, 2020). Recent work has explored biases and heuristics in the scenario process (Schirrmeister et al., 2020), technology forecasting (Bonaccorsi et al., 2020), and Delphi studies (Winkler & Moser, 2016), proposing solutions to mitigate biases or emphasizing the role of the facilitator.

Emotions can also lead to inaccurate predictions. Our mental simulations of the future may appear unrepresentative, essentialized, abbreviated, or decontextualized if our prefeelings do not match the contextual factors or our hedonic response (Gilbert & Wilson, 2007).

Since there are many possibilities for the futures, we need to choose which one to pursue, the one that motivates us to reach or get closer to our desired future. To imagine different possibilities, we need to use our creative thinking, which allows for a partial detachment from reality in order to achieve transformative futures. Without creativity, the future we are imagining is just a quantitative analysis of elements (Corazza, 2017; 2024).

5. Creativity and Futures Studies

We have already established the fact that there are important commonalities and differences between creativity and anticipa-

tion (Corazza, 2017). Our further argument is that a fertile cross-pollination between creativity studies and futures studies is a must (Corazza, 2024). In fact, competence in creativity is crucial for futurists, whose role is to defy the tendency to view the future as merely an extension of present trends, often referred to as the "business-as-usual" prediction. This narrow approach typically focuses on the most probable future and is often used in short- to medium-term forecasting based on quantitative measures. However, foresight, which requires envisioning a wide range of possible futures, including those that may seem improbable, demands a more imaginative approach. Futurists should therefore be equipped not only with foresight methodologies but also with creative skills (Corazza, 2016; Glâveanu et al., 2020; Vinchon et al., 2023) to think beyond conventional limits and explore diverse future scenarios. For instance, tools such as the Futures Wheel, Three Horizons, and Wild Cards and Weak Signals benefit greatly from creativity in identifying unforeseen connections, imagining innovative pathways, and generating surprising ideas. Creativity also plays a critical role in methods like Design Fiction and Art-Based Methods, where the imaginative construction of future narratives or the use of symbolism and metaphor can lead to compelling and insightful visions.

On the other hand, competence in Futures Studies can significantly enhance the creative process by affecting its potential (Corazza & Glâveanu, 2020). All stages of the creative process, as outlined in the DA VINCI model (Corazza & Agnoli, 2022), can benefit from using the concepts and tools of foresight and anticipation. DA VINCI here is an acronym standing for the five fundamental states of the creative process: Drive – Attention and Volition; Information; Novelty generation; Creativity estimation; Implementation. For example, in the Drive – Attention and Volition stage, foresight can help in motivating creative efforts by placing attention onto systemic variables, small signals in society, urgent and crucial matters. In the Information stage, foresight aids in gathering relevant future-oriented data, making informed decisions about what information to prioritize, and providing inspiration from imagined futures. During Novelty generation, an orientation towards future possibilities enhances the creative actor's ability to anticipate opportunities

and generate original ideas with long-term potential. The Creativity estimation stage particularly benefits from foresight, as it involves imagining various future scenarios: the wider the set of available futures, the larger the ability of the creator to find value in her ideas, even when others fail to see it. Finally, in the Implementation stage, foresight is critical in transforming ideas into innovations, anticipating their effects, and guiding decisions that may determine the success of both private and public entities. Thus, integrating creativity and Futures Studies leads to more nuanced, diverse, and comprehensive perspectives on potential futures and enhances the overall creative process.

6. AI and Futures Studies

The cross-pollination between Creativity Studies and Futures Studies is not merely an opportunity or a generic scientific interest in interdisciplinarity, but an urgent necessity in our society (Corazza, 2024). Given the strong connection between these two disciplines, the purpose of this chapter is to explore the use of AI technologies in Futures and Foresight methodologies, with a specific focus on their impact on scenario building. First and foremost, it is fundamental to consider the importance that AI demonstrates in supporting humans during the environmental scanning phase. It is possible to envision co-piloted foresight approaches that leverage artificial intelligence to automate information scanning and data analysis, allowing the human component to focus on more creative and imaginative tasks (Brandtner & Mates, 2021). There is already a plethora of emerging applications that leverage AI to support trend and signals analysis, e.g. Accenture Foresight App or Supertrends (Casoni, 2023).

Scenario planning has been defined in various ways (Porter, 1985; Schwartz, 1996; Ringland, 1998; Schoemaker, 1995), but the main characteristic of this process is that scenarios are not predictions or forecasts. The aim is not to get the future "right," but to challenge current perceptions of the future and to develop stories that highlight aspects that might otherwise be overlooked (Chermack et al., 2001). Both scenario building and consequential strategic planning require crea-

tivity; it is necessary to adopt a proactive and creative mindset (Bourmistrov & Åmo, 2021) to experiment with alternative courses of action.

Creative storytelling and written narratives are the preferred tools for developing plausible future scenarios, and various experiments have been conducted to test the contribution of AI tools to the ideation of scenario narratives and speculative fictions.

AI's usefulness is particularly evident in the early stages of writing, as it encourages divergent thinking and provides unexpected solutions; writers can choose to incorporate, or not, these suggestions into their final work. AI is identified as an "irritating partner that provides food for thought" (Tost et al., 2023) and, despite the risk of biases, extreme importance is given to the active role of writer in shaping the narrative.

In collaborative processes, brainstorming can often be intimidating, with a tendency for conformity (conformity bias); AI interactions can provide a judgment-free setting (Clark et al., 2018). This feedback is especially noted in interactions with "storybuilding bots" that help people reflect on and express their perspectives on certain topics through dialogue (Halperin et al., 2023).

Efforts to use Generative AI as a Red Team ("devil's advocate") to generate alternative, innovative, and contradictory scenarios reveal its limitations in creating dystopian narratives. Overcoming these ethical built-in limitations through prompt engineering can be resource-intensive and time-consuming (Garvey & Svendsen, 2023).

It remains crucial to create alignment between automation and human contribution by tailoring the level of collaboration (Yannakakis et al., 2014; Moruzzi & Margarido, 2024) and preserving the learning effects—and the development of Futures Literacy skills—that scenario planning as a collective practice has on participants (Rhisiart et al., 2015). An interesting research perspective could involve the use of AI as a prompter for scenario dramatization. Further, it should be noted that recent work has been carried out to bring together both foresight methodologies and generative AI in the creative process, which is then properly identified as the Cyber-Creative Process (Corazza, 2025).

7. Custom GPTs for circular and sustainable design

The integration of emerging AI technologies into the domain of Futures Studies and Design is progressively on the rise. These technologies have the capability to analyze complex data, simulate future scenarios, and support decision-making processes. The introduction of GPT-4 by OpenAI has enabled the customization of large language models (custom GPTs) through system instructions and the submission of individual documents to the model (Achiam et al., 2023).

Custom GPT acts as an AI-powered tool that augments the designer's creativity and strategic foresight capabilities. It provides a platform where human intuition and creativity are combined with the analytical power of AI, leading to more comprehensive and forward-thinking design solutions.

A custom GPT called Circular Design Helper has been designed to support students and designers in developing projects and products that align with circular economy principles.

The custom GPT integrates a wide range of specialized knowledge from documents on EU regulations, materials certifications and resources from leading organizations like the Ellen MacArthur Foundation. This integration is crucial as it aligns with the interdisciplinary nature of Futures Studies, which combines elements from various disciplines to anticipate and shape future scenarios. By providing designers with this diverse knowledge base, the GPT encourages a holistic understanding of the factors influencing sustainability and circular economy practices.

Circular design practices are increasingly recognized as vital components in the pursuit of a sustainable and resilient future. This paradigm shift from a linear "take-make-dispose" model to a circular approach emphasizes the importance of designing products and systems that minimize waste, optimize resource use, and extend product life cycles (Ellen MacArthur Foundation, 2013). Circular design not only addresses the environmental challenges posed by resource depletion and waste accumulation but also promotes economic efficiency and innovation.

The implementation of circular design practices is not without its challenges, particularly in terms of the knowledge and

skills required by designers. This is where AI-generated tools, such as the custom GPT Circular Design Helper, play a critical role. These tools provide designers with insights into sustainable materials, regulatory frameworks, and innovative design methodologies, among others information. By leveraging AI, designers can enhance their understanding of circular principles and apply them effectively in their work. By integrating circular principles into the design process, designers can create products that are easier to recycle, refurbish, or repurpose, thereby contributing to a more sustainable and equitable global economy.

The custom GPT Circular Design Helper offers valuable support in navigating the complexities of regulations in sustainability and circularity, providing designers with data-driven insights, assessments and practical guidance. For instance, designers can use AI to explore alternative materials or to model the environmental impact of different design choices. Additionally, AI can facilitate collaboration across disciplines by integrating diverse knowledge streams, enabling designers to develop holistic solutions that address multiple dimensions of sustainability.

In conclusion, both Futures Studies and Design share a focus on strategic problem-solving and innovation. The custom GPT assists designers in identifying and addressing complex challenges related to sustainability and circularity. It provides data-driven insights and practical advice on reducing material waste, selecting sustainable materials, and designing products with lifecycle considerations in mind. This aligns with the Futures Studies methodology of using strategic foresight to navigate potential futures, enabling designers to develop solutions that are not only innovative but also resilient and adaptable to future changes.

8. Conclusions

We intend to highlight the vital intersection between psychological correlates, human creativity, Artificial Intelligence (AI), and foresight in the pursuit of sustainable futures. This interdisciplinary approach, combining Futures Studies, cognitive

psychology, creativity, and AI, holds the promise to become a robust epistemological toolkit for designers, particularly in circular and sustainable design.

The historical evolution of Futures Studies demonstrates its increasingly interdisciplinary nature, which has led to more sophisticated methodologies capable of addressing complex global challenges. However, individual differences must be taken into account in all human-driven activities, and it is for this reason that we consider that the study of the psychological correlates to future thinking is such an important element. Also, the chapter emphasizes the critical role of creativity in foresight, where imaginative approaches are necessary to envision diverse futures beyond conventional predictions. Conversely, Futures Studies enriches the creative process by providing future-oriented insights that guide decision-making at every stage. Further, by integrating AI into these methodologies, especially in the context of scenario building and environmental scanning, the ability to anticipate and navigate future uncertainties could be greatly enhanced. AI tools, such as the custom GPT we presented, exemplify this integration by augmenting human creativity and foresight, offering tailored support to designers in their efforts to align with circular economy principles. The "Circular Design Helper" custom GPT illustrates how AI can be leveraged to embed sustainability into the design process, ensuring that products are created with their entire lifecycle in mind.

In conclusion, the cross-pollination between psychology, human creativity, AI, and foresight is not merely beneficial but essential for developing the next generation of designers for resilient and sustainable solutions. By combining these elements, designers are better equipped to address the complex challenges of the future, ensuring that their innovations are both forward-thinking and grounded in the principles of sustainability and circularity. This integrated approach ultimately contributes to a more sustainable and equitable global economy.

References

Achiam et al., 2023
Achiam, J., Adler, S., Agarwal, S., Ahmad, L., Akkaya, I., Aleman, F. L., … & McGrew, B. (2023). GPT-4 technical report. *arXiv preprint*. arXiv:2303.08774. https://doi.org/10.48550/arXiv.2303.08774

Bonaccorsi, Apreda & Fantoni, 2020
Bonaccorsi, A., Apreda, R., & Fantoni, G. (2020). Expert biases in technology foresight. Why they are a problem and how to mitigate them. *Technological Forecasting and Social Change*, *151*(4), 119855. https://doi.org/10.1016/j.techfore.2019.119855

Bourmistrov & Åmo, 2021
Bourmistrov, A., & Åmo, B. W. (2021). Creativity, proactivity, and foresight. *Technological Forecasting & Social Change*, *174*(9). https://doi.org/10.1016/j.techfore.2021.121215

Brandtner & Mates, 2021
Brandtner, P., & Mates, M. (2021). Artificial intelligence in strategic foresight – Current practices and future application potentials. In *ICEME '21: Proceedings of the 2021 12th International Conference on E-business, Management and Economics* (pp. 75–81). https://doi.org/10.1145/3481127.3481177

Burns et al., 2019
Burns, P., McCormack, T., Jaroslawska, A., Fitzpatrick, Á., McGourty, J., & Caruso, E. M. (2019). The development of asymmetries in past and future thinking. *Journal of Experimental Psychology: General*, *148*(2), 272–288. https://doi.org/10.1037/xge0000464

Casoni, 2023
Casoni, G. (2023). *Report on digital platforms to support strategic foresight*. SFIDA-MICS Project Deliverable.

Chermack et al., 2001
Chermack, T. J., Lynham, S. A., & Ruona, W. E. A. (2001). A review of scenario planning literature. *Futures Research Quarterly*, *17*(2), 7–31.

Clark et al., 2018
Clark, E., Tan, C., Ross, A., Ji, Y., & Smith, N. A. (2018). Creative writing with a machine in the loop: Case studies on slogans and stories. In *Proceedings of the 23rd ACM Conference on Intelligent User Interfaces (IUI'2018)* (pp. 329–340).

Corazza, 2016
Corazza, G. E. (2016). Potential originality and effectiveness: The dynamic definition of creativity. *Creativity Research Journal*, *28*(3), 258–267. https://doi.org/10.1080/10400419.2016.1195627

Corazza, 2017
Corazza, G. E. (2017). Creativity and anticipation. In R. Poli (Ed.), *Handbook of Anticipation. Theoretical and Applied Aspects of the Use of Future in Decision Making* (pp. 761–772). Springer.

Corazza, 2020
Corazza, G. E. (2020). Alfred North Whitehead. In V. Glăveanu (Ed.), *The Palgrave encyclopedia of the possible*. Palgrave Macmillan.

Corazza, 2024
Corazza, G. E. (2024). Creativity and Futures Studies. In R. Poli (Ed.), *Handbook of Futures Studies* (pp. 131–144). Edward Elgar Publishing.

Corazza, 2025
Corazza, G. E. (2025). *The cyber-creativity process: How humans co-create with Artificial Intelligence*. Palgrave Macmillan.

Corazza & Agnoli, 2022
Corazza, G. E., & Agnoli, S. (2022). The DA VINCI model for the creative thinking process. In T. Lubart, et al. (Eds.), *Homo Creativus* (pp. 49–67). Springer.

Ellen MacArthur Foundation, 2013
Ellen MacArthur Foundation. (2013). *Towards the circular economy Vol. 1: An economic and business rationale for an accelerated transition*. https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an

Faiella & Corazza, 2025
Faiella, A., & Corazza, G. E. (2025). Cognitive mechanisms in foresight: A bridge between psychology and futures studies. *Futures*, *166*, 103547.

Garvey B. & Svendsen, 2023
Garvey, B., & Svendsen, A. (2023). Can generative-AI (ChatGPT and Bard) be used as red team avatars in developing foresight scenarios? *Analytic Research Consortium (ARC) August 2023.* https://ssrn.com/abstract=4541396 or http://dx.doi.org/10.2139/ssrn.4541396

Gilbert & Wilson, 2007
Gilbert, D. T., & Wilson, T. D. (2007). Prospection: Experiencing the future. *Science*, *317*(5843), 1351–1354. https://doi.org/10.1126/science.1144161

Glăveanu et al., 2020
Glăveanu, V. P., Hanchett Hanson, M., Baer, J., Barbot, B., Clapp, E. P., Corazza, G. E., Hennessey, B., Kaufman, J. C., Lebuda, I., Lubart, T., Montuori, A., Ness, I. J., Plucker, J., Reiter-Palmon, R., Sierra, S., Simonton, D. K., Souza Neves-Pereira, M. & Sternberg, R. J. (2020). Advancing creativity theory and research: A sociocultural manifesto. *Journal of Creative Behaviour*, *54*(3), 741–745. https://doi.org/10.1177/1089268020961763

Halperin et al., 2023
Halperin, B. A., Hsieh, G., McElroy, E., Pierce, J., & Rosner, D. K. (2023). Probing a community-based conversational storytelling agent to document digital stories of housing insecurity. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)* (pp. 1–18). ACM. https://doi.org/10.1145/3544548.3581109

Hines, 2020
Hines, A. (2020). When did it start? Origin of the foresight field. *World Futures Review*, *12*(1), 4–11. https://doi.org/10.1177/1946756719889053

Kahn, 1960
Kahn, H. (1960). *On thermonuclear war*. Princeton University Press.

Karniol & Ross, 1996
Karniol, R., & Ross, M. (1996). The motivational impact of temporal focus: Thinking about the future and the past. *Annual Review of Psychology*, *47*(1), 593–620. https://doi.org/10.1146/annurev.psych.47.1.593

Meadows et al., 1972
Meadows, D. H., Meadows, D. L., Randers, J., & Behrens III, W. W. (1972). *The limits to growth: A report for the Club of Rome's project on the predicament of mankind*. Universe Books.

Miller, 2007
Miller, R. (2007). Futures literacy: A hybrid strategic scenario method. *Futures*, *39*(4), 341–362. https://doi.org/10.1016/j.futures.2006.12.001

Moruzzi & Margarido, 2024
Moruzzi, C., & Margarido, S. (2024). A user-centered framework for human-AI co-creativity. In *CHI '24: CHI Conference on Human Factors in Computing Systems*.

Naisbitt, 1982
Naisbitt, J. (1982). *Megatrends: Ten new directions transforming our lives*. Warner Books.

Poli, 2015
Poli, R. (2015). Social foresight. *On the Horizon*, *23*(2), 85–99. https://doi.org/10.1108/OTH-01-2015-0003

Popper, 1957
Popper, K. R. (1957). *The poverty of historicism*. Routledge.

Porter, 1985
Porter, M. E. (1985). *Competitive advantage: Creating and sustaining superior performance*. Free Press.

Rhisiart, Miller & Brooks, 2015
Rhisiart, M., Miller, R., & Brooks, S. B. (2015). Learning to use the future: Developing foresight capabilities through scenario processes. *Technological Forecasting and Social Change*, *101*, 124–133. https://doi.org/10.1016/j.techfore.2014.10.015

Ringland, 1998
Ringland, G. (1998). *Scenario planning: Managing for the future*. John Wiley & Sons Ltd.

Salgado & Berntsen, 2020
Salgado, S., & Berntsen, D. (2020). My future is brighter than yours: the positivity bias in episodic future thinking and future self-images. *Psychological Research*, *84*(7), 1829–1845. https://doi.org/10.1007/s00426-019-01189-z

Schacter et al., 2012
Schacter, D. L., Addis, D. R., Hassabis, D., Martin, V. C., Spreng, R. N., & Szpunar, K. K. (2012). The future of memory: Remembering, imagining, and the brain. *Neuron*, *76*(4), 677–694. https://doi.org/10.1016/j.neuron.2012.11.001

Schirrmeister, Göhring & Warnke, 2020
Schirrmeister, E., Göhring, A., & Warnke, P. (2020). Psychological biases and heuristics in the context of foresight and scenario processes. *Futures & Foresight Science*, *2*(2), e31. https://doi.org/10.1002/ffo2.31

Schoemaker, 1995
Schoemaker, P. J. H. (1995). Scenario planning: A tool for strategic thinking. *Sloan Management Review, Winter*, *36*(2), 25–40.

Schwartz, 1996
Schwartz, P. (1996). *The Art of the long view: Paths to strategic insight for yourself and your company*. Currency Doubleday.

Sharpe, 1996
Sharpe, B. (1996). Three horizons: The Patterning of hope. *Journal of Business Strategy*, *17*(3), 13–25.

Suddendorf & Corballis, 1997
Suddendorf, T., & Corballis, M. C. (1997). Mental time travel and the evolution of the human mind. *Genetic Social and General Psychology Monographs*, *123*(2), 133–168.

Szpunar, Spreng & Schacter, 2014
Szpunar, K. K., Spreng, R. N., & Schacter, D. L. (2014). A Taxonomy of prospection: Introducing an organizational framework for future-oriented cognition. *Proceedings of the National Academy of Sciences*, *111*(52), 18414–18421. https://doi.org/10.1073/pnas.1417144111.

Tost et al., 2023
Tost, J., Gohsen, M., Schulte, B., Thomet, F., Kuhn, M., Kiesel, J., & Stein, B. (2023). Futuring machines: An interactive framework for participative futuring through human-AI collaborative speculative fiction writing. In *Proceedings of the 6th ACM Conference on Conversational User Interfaces* (pp. 1–7).

Vinchon et al., 2023
Vinchon, F., Lubart, T., Bartolotta, S., Gironnay, V., Botella, M., Bourgeois-Bougrine, S., Burkhardt, J. M., Bonnardel, N., Corazza, G.E., Glăveanu, V. & Hanchett Hanson, M. (2023). Artificial Intelligence & Creativity: A manifesto for collaboration. *The Journal of Creative Behavior*, *57*(4), 472–484. https://doi.org/10.1002/jocb.597

Wack, 1985
Wack, P. (1985). *Scenarios: Uncharted waters ahead*. Harvard Business Review.

Weiler, Suchan & Daum, 2010
Weiler, J. A., Suchan, B., & Daum, I. (2010). When the future becomes the past: Differences in brain activation patterns for episodic memory and episodic future thinking. *Behavioural Brain Research*, *212*(2), 196–203. https://doi.org/10.1016/j.bbr.2010.04.013

Wells, 1902
Wells, H. G. (1902). *The Discovery of the Future: A discourse delivered to the Royal Institution on January 24, 1902*. T. Fisher Unwin.

Winkler & Moser, 2016
Winkler, J., & Moser, R. (2016). Biases in future-oriented Delphi studies: A cognitive perspective. *Technological Forecasting and Social Change*, *105*, 63–76. https://doi.org/10.1016/j.techfore.2016.01.021.

Yannakakis, Liapis & Alexopoulos, 2014
Yannakakis, G. N., Liapis, A., & Alexopoulos, C. (2014). *Mixed-initiative Co-creativity*. International Conference on Foundations of Digital Games.

FROM INDIVIDUAL TO ORGANIZATIONAL BRAIN. COMBINING COGNITIVE TRAINING, MINDFULNESS AND ORGANIZATIONAL INNOVATION TO ENHANCE SUSTAINABLE FORESIGHT CAPABILITIES OF SMES

Giorgio Casoni, Flaviano Celaschi*, Valentina De Matteo**

1. Introduction

Strategic Foresight (SF) is increasingly recognized as a critical skill for navigating the complexities and uncertainties of the modern world. In rapidly evolving environments, the ability to anticipate and prepare for future challenges and opportunities has become essential. SF involves systematically envisioning potential, probable, and preferred futures, identifying emerging trends, and developing strategies to shape desired outcomes. This proactive approach enhances decision-making and resilience in the face of uncertainty.

The hypothesis of the SFIDA (Strategic Foresight for Innovation Design Augmentation) project posits that the development and growth of Made in Italy must address two key challenges: circularity and sustainability, alongside the ability of businesses to balance tradition (heritage, identity, history, and storytelling) with Futures Literacy (FL) and long-term strategic vision. Field research and literature suggest a stereotype that Italian SMEs often operate with short-term perspectives, unable to capitalize on rapid market changes. A critical growth factor for these SMEs lies in comprehending and utilizing digital technologies and artificial intelligence, particularly in advancing future-oriented reasoning. This study explores the hypothesis that a structural deficiency in critical thinking about futures, observed in SME operators, correlates with inefficient use of both individual cognitive abilities and organizational cognition.

The paper proposes enhancing foresight in SMEs by combining cognitive training at the individual level with organizational innovation at the systemic level. This dual approach fosters an "organizational brain," where individual foresight is scaled and integrated into collective organizational intelligence, enabling

**Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

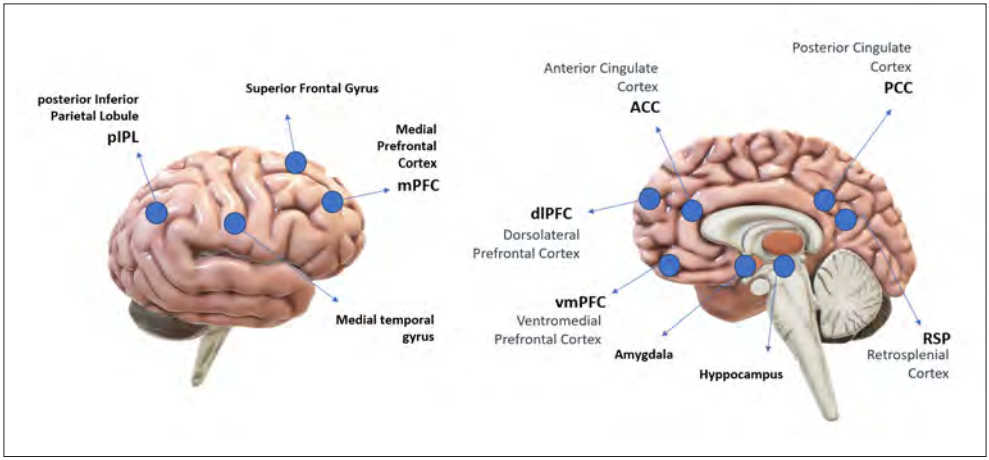
SMEs to become more agile and adaptable to future market shifts. Cognitive training enhances individual foresight, but the challenge is scaling this to the organizational level. Organizational innovation—through methods like design thinking, scenario planning, and co-creation—enables these cognitive gains to be applied to strategic foresight, fostering long-term resilience in SMEs (Teece, 2007).

The first part of the paper examines the neural correlates mechanisms, cognitive training, and mindfulness practices related to foresight, focusing on brain regions like the prefrontal cortex, hippocampus, and anterior cingulate cortex, which are crucial for processing future-oriented information. The second part addresses organizational cognition, a concept that has evolved over the past fifty years from computational to systemic approaches. These systemic models emphasize the role of social organization in shaping cognitive processes within organizations (Nobre et al., 2015; Nobre et al., 2008; Secchi & Cowley, 2018).

By integrating individual cognitive capabilities with organizational resilience, SMEs can better anticipate and prepare for future challenges. This integration is encapsulated in the Foresight Cognition Development Model (FCDM), which is presented as a comprehensive framework for enhancing strategic foresight within organizations.

2. Effectiveness of cognitive training and mindfulness in strengthening futures literacy

The link between neural mechanisms and SF opens new avenues for enhancing predictive skills, with significant implications for strategic planning, decision-making, and managing uncertainty. Understanding the cognitive functions and brain areas involved in predicting future scenarios, such as the prefrontal cortex (PFC), offers insights into the synergy between brain mechanisms and SF applications. The PFC, particularly the dorsolateral prefrontal cortex (dlPFC), medial prefrontal cortex (mPFC), and ventromedial prefrontal cortex (vmPFC), is critical for problem-solving, cognitive flexibility, and evaluating future rewards (Schacter et al., 2007; Miró-Padilla et al., 2019).



1. Brain areas involved in SF.
All images are reproduced in color in the online edition of the book.

Additionally, the anterior cingulate cortex (ACC) plays a key role in monitoring errors and emotional responses, which are essential for adjusting strategies under uncertainty (Botvinick et al., 2004). Memory functions, particularly working and episodic memory, also contribute to future-oriented thinking by engaging areas like the hippocampus and posterior parietal lobule (Hill & Emery, 2013; Weiler et al., 2010). Cognitive training and mindfulness have been identified as effective tools for strengthening these domains and improving SF (Gazzaniga et al., 2013; Goel, 2007).

This neural foundation connects directly to FL, a critical capability that relies heavily on cognitive flexibility, attentional control, and stress management. FL, defined as the ability to anticipate and prepare for potential futures, benefits from interventions like cognitive training and mindfulness. These methods are evaluated not only by statistical significance but also through effect size, a measure that quantifies the practical importance of cognitive and behavioral improvements. This approach underscores the real-world relevance of these interventions in enhancing strategic foresight and future-oriented decision-making. Figure 1 illustrates the involvement of these brain areas during SF, while the following sections will delve deeper into the specific cognitive functions facilitated by these regions.

Tab. 1. Effect size in cognitive training.

COGNITIVE TRAINING EXERCISE	EXERCISE FUNCTION	NEURAL CORRELATES	SCIENTIFIC REFERENCE	JOURNAL NAME
Flanker	Focus on tasks in distracting environments, and avoid traps or mistakes under pressure	GFi, dlPFC, ACC, Pipl	Davelaar, E. J. (2013)	Frontiers in Psychology
Cocktail Party	Analysis and selection of relevant information and inhibition of distractions	IFG, DLPFC, IPL	Lanzilotti C., et al. (2022)	Plos One
N-Back	Cognitive flexibility		Li, W., et al. (2021)	Scientific Reports
	Cognitive flexibility	IPC, ACC, dlPFC	Miró-Padilla A, et al. (2019)	Brain Imaging and Behavior
Task Switching	Managing multi-tasking tasks, adapting to rapid changes	PFC, ACC	Toovey, B. R. W., et al. (2021)	Frontiers in Psychology
Stroop	Control skills, interference management and inhibition of automatisms	-	Burger L., et al. (2020)	Experimental Aging Research
Method of loci	Spatial memory, executive functions, metacognition	Hippocampus, RSP, mPFC, dlPFC	Dresler, M., et al. (2017)	Neuron
Spatial CWM	Spatial working memory, ability to use the same brain areas for multiple tasks at once	dlPFC, ACC	Chein, J. M. & Morrison, A. B. (2010)	Psychonomic Bulletin and Review

2.1. Cognitive training

Cognitive training involves systematic methods aimed at improving cognitive functions such as memory, attention, and executive control by leveraging neuroplasticity. Key tools include serious games, which combine educational and therapeutic objectives with entertainment, making cognitive exercises more engaging and effective (Gobet & Sala, 2023). As demonstrated in several studies, the effect size plays a crucial role in assessing the practical significance of cognitive training outcomes.

In cognitive science, effect size refers to the magnitude of the intervention's impact on the target cognitive functions compared to a control group or a pre-training baseline. This is especially important for determining if a change is meaningful and substantial rather than merely statistically significant.

IMPACT FACTOR	EFFECT SIZE							N
	Parameters considered	η^2	d	r^2	F	p	t	
4,232	Reaction Time	0,86			66,63	<0.001		12
	Accuracy	0,568			14,33	<0.001		
3,752	Cortical attivation					p <0.05		74
	Behavioural				72,2	<0.001		
4,997	Behavioural	130			21,7	<0.001		148
3,2	Reaction Time				11,34	<.001		54
	Accuracy				4,01	<.007		
	Neural attivation					<.001		
4,232	Behavioural	0,05			3,84	0,03		36
1,652	Behavioral	0,53			101,83	<.001		93
18,688	Behavioral	0,58		0,3	33,2	<0.001		74
	Connectivity			0,26		0,02		
4,412	Temporary memory		1.420			<0,005	4,49	42
	Cognitive control		570			0,39	1,81	
	Fluid intelligence			0,24		0,41	0,24	

The size effect is measured using several key statistical parameters that quantify the magnitude and practical significance of an intervention's impact. One of the most common metrics is Cohen's d, which measures the standardized difference between two means, typically comparing pre- and post-intervention performance. Larger values of Cohen's d indicate a stronger effect. Another key parameter is eta-squared (η^2), which reflects the proportion of variance in a dependent variable attributable to the intervention, with higher values suggesting a more substantial impact. R-squared (r^2) is used to determine the percentage of variance in the outcome explained by the intervention, while F-statistics assess whether the variation between group means is significantly larger than within-group variation, indicating whether the intervention has a meaningful effect. Additionally,

p-values are used to determine statistical significance, with values below 0.05 typically indicating that the results are unlikely to be due to chance. Finally, t-statistics measure the difference between groups relative to the sample variability, further validating the size of the effect. Together, these parameters offer a comprehensive view of both the statistical and practical significance of an intervention.

A detailed analysis of table 1 reveals the effect size parameters associated with various cognitive training exercises. For example, Flanker and Cocktail Party tasks demonstrated substantial effect sizes with eta-squared (η^2) values of 0.568 and Cohen's d values of 1.420, respectively, indicating significant improvements in focus, information selection, and multitasking capabilities. These findings suggest that cognitive training, particularly for executive function and attentional control, can meaningfully enhance FL by equipping individuals to manage complex information and foresee multiple future scenarios (Helber et al., 2012).

Other cognitive training exercises, such as the N-Back (behavioral) task and Task Switching, showed more moderate effect sizes, indicating beneficial but less dramatic cognitive improvements. These differences emphasize the importance of selecting targeted cognitive training exercises that align with specific learning objectives, especially when aiming to build foresight and strategic planning capabilities. The effect size metrics—such as η^2, Cohen's d, R-squared (r^2), F-statistics, and p-values—provide critical insights into the varying degrees of effectiveness across different exercises (Brosschot, 2011).

2.2. Mindfulness

Mindfulness, defined as the practice of paying mindful, nonjudgmental attention to the present, has shown significant promise in enhancing cognitive flexibility, stress management, and emotional regulation—key components of FL. Initially, mindfulness was studied for its impact on emotional well-being and stress reduction (Brown & Ryan, 2003; Kabat-Zinn, 2003). However, growing evidence suggests that mindfulness also improves cognitive functions such as working memory, attention, and problem-solving, which are essential for strategic foresight.

Mindfulness enables individuals to step out of "autopilot" mode, fostering greater awareness of bodily stress signals and

reducing emotional reactivity (Williams et al., 2008). This shift in perspective is particularly useful in futures thinking, where maintaining cognitive flexibility and an open-minded approach to uncertainty is crucial. Studies, such as those by Lim et al. (2018), using dynamic functional connectivity fMRI, demonstrate that individuals with higher mindfulness exhibit enhanced connectivity between brain networks associated with task readiness, further supporting the cognitive benefits of mindfulness for strategic planning.

The effect size of mindfulness interventions has been analyzed in several cognitive and behavioral domains. Table 2 highlights how mindfulness practices yield effect sizes across various outcomes, with large Cohen's d values (e.g., 0.641) for stress reduction and improvements in cognitive flexibility, underscoring the substantial and practical significance of mindfulness training in enhancing performance and reducing stress. Mindfulness interventions, thus, prepare the mind for effective cognitive training by creating a calm and focused mental state, enhancing the individual's capacity for FL (Jha et al., 2010; Evans et al., 2009).

In both cognitive training and mindfulness, the effect size offers a critical lens through which the practical utility of interventions can be assessed. Key statistical parameters such as eta-squared (η^2), Cohen's d, and p-values measure not just whether changes are statistically significant but whether they are impactful enough to justify adoption in educational and practical settings. High eta-squared values indicate that a significant portion of the variance in cognitive performance can be attributed to intervention, while Cohen's d measures the magnitude of improvement from pre- to post-intervention periods.

For instance, exercises like Flanker and Cocktail Party, with high η^2 and Cohen's d values, demonstrate robust cognitive improvements, suggesting that such training can meaningfully enhance individuals' ability to anticipate and navigate future challenges. In contrast, more moderate effect sizes observed in exercises like N-Back (reaction time) suggest a more limited, though still valuable, impact. Similarly, in mindfulness research, strong effect sizes for stress reduction and cognitive flexibility suggest that these practices significantly improve individuals' mental readiness for future planning and decision-making under uncertainty (Brown & Ryan, 2003; Kabat-Zinn, 2003).

Tab. 2. Effect size in mindfulness.

PROTOCOL	FUNCTION	NEURAL CORRELATES	EVIDENCE SCIENTIFIC	JOURNAL NAME
Mindfulness, concentration, visualization (loving-kindness)	Executive functions	-	Helber, C., et al. (2012)	Innovative Higher Education
Meditation (breathing, relaxation, focusing)	Learning, memory	-	Hall, P. D. (1999)	Journal of Black Studies
Mindfulness of Breathing	Stress	Amygdala, sgACC	Taren, A. A., et al. (2015)	Social Cognitive and Affective Neuroscience Advance Access
MBSR	Stress, positive/ negative feelings, self-esteem	-	Żołnierczyk-Zreda, D., et al. (2016)	Occupational medicine
Mindfulness of Breathing	Attention	ACC, insula, TPJ, SPL, dlPFC	Dickenson, J., et al. (2013)	Social cognitive and affective neuroscience
MBCT	Cognitive flexibility, memory	-	Heeren, A., et al. (2009)	Behaviour research and therapy
MBSR	Functional connectivity: executive functions	PCC DLPFC	Kral, T. R. A., et al. (2019)	Social cognitive and affective neuroscience
Meditation	Cognitive flexibility	-	Moore, A., & Malinowski, P. (2009)	Consciousness and cognition
Mindfulness of breathing	Inhibitory control, response monitoring	-	Pozuelos, J. P., et al. (2019)	Progress in brain research
MBSR variant 20min	Acceptance	Limbic system, anterior insula	Kirk, U., et al. (2016)	NeuroImage

IMPACT FACTOR	EFFECT SIZE								
	Parameters	η^2	d	r^2	F	r	p	t	N
2,81	Behavioural					0,82	<0.01		31
1,1	Behavioural				6,41		<0.014		56
4,2	Functional connettivity						0,05		130
	Cortisone					-0,39	0,049		
	Cortisolo				0,783		0,385		
5,629	Work-related stress		0,72		20,4		<0.001		144
	Negative affect				95,77		<0.0001		
	Positive affect				19,3		<0.001		
	Self-esteem				120.5		<0.001		
4,235	SPL							4,42	31
	TPJ							4,14	
	GFI							3,38	
5,321	Autobiographical memory test	0,6			50,9		<0.001		36
	Hayling Task	0,52			37,24		<0.001		
	GoStop	0,00			0,07		0,80		
4,235	Functional connettivity PCC-IDLPFC						0,03	2,22	85
	Functional connettivity PCC-rDLPFC						0,02	2,34	
2,728	Kentucky Inventory of Mindfulness Skills						<0.001	6,40	50
	Stroop Test						<0.001	3,92	
	d2-Test						<0.001	5,68	
2,624	Go/no-go	0,114					0,047	4,22	36
	Neural attivation: N2	0,146					0,004	9,57	
	Neural attivation: ERN	0,124					0,04	4,53	
5,7	Behavioural						<0.05		50
	Neural attivation						0,004	3,14	

Both cognitive training and mindfulness play crucial roles in supporting the development of FL, particularly by enhancing cognitive flexibility, focus, stress management, and decision-making under uncertainty. The concept of effect size provides a more nuanced understanding of the real-world effectiveness of these interventions. Rather than relying solely on statistical significance, the effect size offers insight into the magnitude of improvement, guiding the selection of methods that yield substantial and meaningful cognitive and behavioral benefits.

Through the analysis of effect size, it becomes clear that cognitive training exercises like Flanker, Cocktail Party, and Stroop produce strong cognitive gains, equipping individuals to manage complex, future-oriented tasks. Similarly, mindfulness practices significantly reduce stress and improve cognitive flexibility, preparing the mind for strategic foresight and enhancing individuals' ability to navigate future uncertainties. Both interventions, therefore, contribute meaningfully to FL by enhancing the mental skills necessary for anticipating, planning, and managing future possibilities.

3. From human to system capacitation. Organizational cognition

While cognitive training and mindfulness enhance individual foresight, scaling these gains to an organizational level presents a key challenge. Organizational innovation plays a crucial role in addressing this challenge by leveraging processes such as design thinking, scenario planning, and co-creation, which allow SMEs to harness individual foresight for collective strategic action. These frameworks enable organizations to foster long-term strategic foresight, ensuring resilience in the face of uncertainties by promoting continuous learning and sustainability (Teece, 2007). Sustainability, in this context, is achieved through inclusive knowledge-sharing practices, the development of collective intelligence, and equitable access to decision-making processes.

One of the most critical challenges in scaling foresight capabilities within enterprises is the transformation from rigid hierarchical structures to interconnected networks of actors

(Alexander et al., 2023). Structured innovation processes, such as design thinking and scenario building, facilitate cross-functional collaboration, ensuring that insights from individual cognitive training are applied to organizational challenges (Brown, 2009; Schoemaker, 1995). As a result, organizational innovation becomes a mechanism for transforming individual foresight into a shared resource, preparing SMEs for future market disruptions and technological shifts (Secchi et al., 2022).

The concept of "habits design" (James, 2023) further bridges the gap between individual cognitive improvements and organizational foresight by creating routines that align individual strengths with organizational goals. Shared habits design embeds foresight into daily decision-making, enabling SMEs to remain agile and adapt quickly to emerging trends (Cowley & Secchi, 2022; Weick, 1995). By institutionalizing foresight through regular workshops and participatory scenario-building, these habits transform foresight from an individual skill into an organizational competency (Tsoukas & Shepherd, 2004).

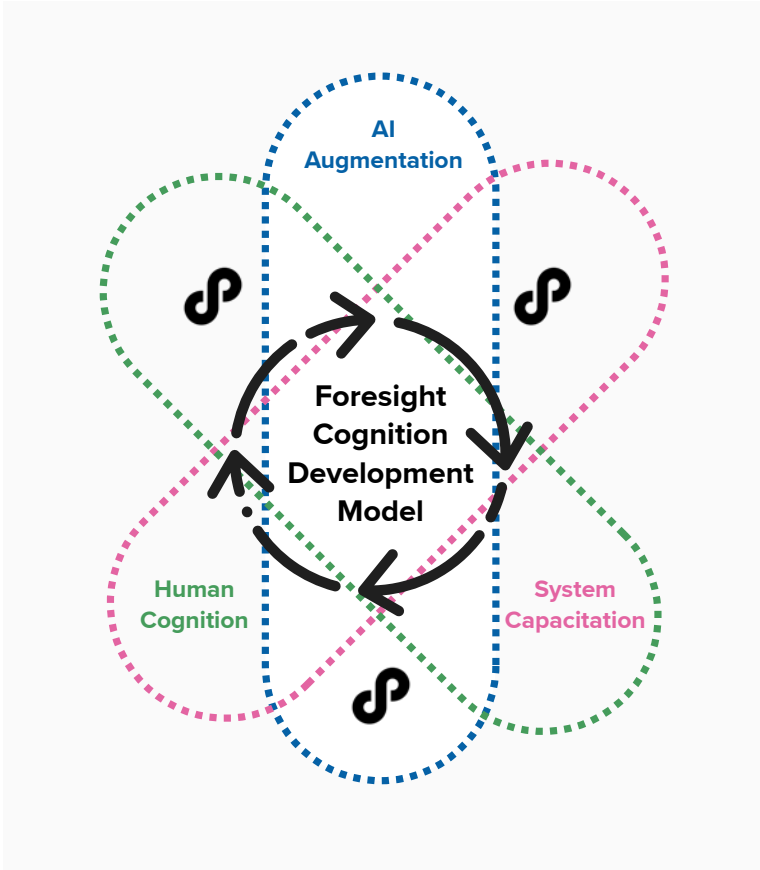
The combination of cognitive training and mindfulness together with organizational innovation culminates in rethinking enterprises as a brain (Yazici, 2022) and considering the system itself as a collective cognitive entity capable of foresight at an organizational level. This model draws on the work of Simon (1997) and other scholars who emphasize the importance of integrating individual and collective cognitive processes within organizations. From SMEs' perspective, the brain represents the integration of individual foresight capabilities with structured innovation processes and shared habits that enable the organization to act with greater anticipatory capacity.

The enterprise brain is characterized by its ability to process information, generate insights, and make decisions in a manner that reflects the collective intelligence of the organization. By developing and using it, SMEs can transform themselves into foresight-driven entities capable of navigating the complexities of modern markets. This approach aligns with recent research on distributed cognition, which highlights the role of collective intelligence in enhancing organizational performance (Hutchins, 1995; Secchi et al., 2022).

4. An integrated view for organizations. Foresight Cognition Development Model (FCDM)

Considerations above can be integrated and summarized in the Foresight Cognition Development Model (FCDM) made of the interaction of three elements: human cognition, system capacitation, and Artificial Intelligence (AI) augmentation. Although the topic of artificial intelligence has not been centrally addressed in this paper, its current and potential importance for organizations, including SMEs, cannot be overlooked. AI presents significant opportunities for SMEs to foster innovation in an increasingly complex and technologically advanced landscape (Paul et al., 2023).

As shown in figure 2, Human cognition refers to the mental processes of individuals within the organization, encompassing perception, memory, learning, decision-making, and problem-solving by cognitive training and mindfulness. These cognitive functions are foundational to organizational performance, as they enable individuals to interpret information, generate knowledge, and make informed decisions. However, in the context of organizational cognition, human cognition transcends the individual level, becoming a collective cognitive process, definable as System Capacitation. This involves the sharing and integration of knowledge across the organization, where the cognitive abilities of individuals are networked, creating a distributed intelligence that enhances the organization's overall ability to process information and respond to challenges of complex environments. AI Augmentation enhances the cognitive functions of individuals and the organization as a whole by leveraging artificial intelligence technologies. AI systems are capable of processing vast amounts of data, identifying patterns, and generating insights that would be beyond the capacity of human cognition alone. AI augmentation frees up human cognitive resources for higher-order thinking and creative problem-solving, thereby amplifying the organization's overall cognitive capacity. Together, these elements are interdependent: human cognition provides the creative, intuitive, and contextual understanding necessary for decision-making. System capacitation ensures the infrastructure and processes are in place to support cognitive functions and to enable enterprise



2. Foresight Cognition Development Model (FCDM).

brain by leveraging collective intelligence; AI augmentation enhances and scales these capabilities, driving the organization's ability to process complex information, innovate and support decision-making processes towards possible futures. The effectiveness and sustainability of this model is based on the design of shared habits, (∞ icon), collective routines, and practices that circularly spread within the organization, harmonize the interaction between human and machine cognition, ensuring a cohesive and aligned organizational behavior aimed at achieving strategic goals. Through this process, the model enables the sustainable development of foresight cognition, driving continuous innovation, strategic foresight, and informed decision-making, ensuring that the organization evolves with both its internal needs and external complexities.

5. Conclusions

This study provides a comprehensive examination of Strategic Foresight (SF) as a critical competency for navigating the complexities and uncertainties inherent in contemporary environments, with a specific focus on Made in Italy SMEs. The investigation reveals that, in the face of rapidly evolving market dynamics and technological advancements, these enterprises must reconcile their traditional values with Futures Literacy (FL) to enhance their strategic planning and decision-making processes.

The research supports the hypothesis that a significant challenge for the growth and sustainability of Made in Italy lies in addressing both circularity and sustainability, while simultaneously harnessing the potential of advanced cognitive, artificial intelligence and technological tools. The prevalent stereotype that Italian SMEs operate with a predominantly short-term perspective is challenged by postulating that there is substantial room for improvement in leveraging rapid market accelerations and exponential growth opportunities.

Our analysis underscores the importance of integrating cognitive training at the individual level with organizational innovation at the systemic level to foster an enterprise brain. This approach involves scaling up individual foresight capabilities

and embedding them into the organization's collective intelligence. By adopting structured innovation processes such as design thinking, scenario planning, and co-creation, SMEs can transform individual cognitive gains into a strategic asset that enhances their agility and adaptability in the face of future uncertainties.

The exploration of neural mechanisms and cognitive processes related to SF provides valuable insights into the underlying brain functions that support strategic planning and decision-making. The study highlights key brain regions, including the prefrontal cortex, hippocampus, and anterior cingulate cortex, which are crucial for future-oriented thinking and cognitive flexibility. By applying cognitive training and mindfulness practices, which have been shown to enhance neural efficiency and cognitive performance, organizations can improve their strategic foresight capabilities.

Furthermore, the investigation into organizational cognition reveals that the integration of individual cognitive strengths into collective organizational practices is essential for developing robust foresight capabilities. The shift from traditional computational models to systemic approaches, which emphasize the impact of social organization on cognitive processes, supports the development of a foresight framework that fosters long-term strategic planning.

The proposed Foresight Cognition Development Model (FCDM) offers a framework for understanding the interplay between human cognition, system capacitation, and AI augmentation. Human cognition encompasses the mental processes of individuals, which are critical for decision-making and problem-solving. System capacitation involves the technological and structural infrastructures that support and optimize these cognitive functions. AI augmentation enhances cognitive capabilities by leveraging advanced technologies to process data, identify patterns, and generate insights, thereby amplifying the organization's cognitive capacity.

Future research should focus on further refining the FCDM and exploring additional methodologies to enhance foresight capabilities across various organizational contexts. By advancing our understanding of the interactions between cognitive processes, organizational structures, and technological tools,

we can better equip SMEs to anticipate and respond to emerging challenges and opportunities in an increasingly dynamic environment.

References

Alexander et al., 2023
Alexander, R., Pember, R., Press, J., & Swatt, K. (2023). *A design-driven guide for entrepreneurs: Strategies for starting up in a multiverse*. Routledge.

Botvinick et al., 2004
Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences*, *8*(12), 539–546. https://doi.org/10.1016/j.tics.2004.10.003

Brosschot, 2010
Brosschot, J. F. (2010). Markers of chronic stress: Prolonged physiological activation and (un)conscious perseverative cognition. *Neuroscience & Biobehavioral Reviews*, *35*(1), 46–50. https://doi.org/10.1016/j.neubiorev.2010.01.004

Brown & Ryan, 2003
Brown, K. W., & Ryan, R. M. (2003). The benefits of being present: Mindfulness and its role in psychological well-being. *Journal of Personality and Social Psychology*, *84*(4), 822. https://doi.org/10.1037/0022-3514.84.4.822

Brown, 2009
Brown, T. (2009). *Change by design: How design thinking creates new alternatives for business and society*. Harper Business.

Burger et al., 2020
Burger, L., Fay, S., Angel, L., Borella, E., Noiret, N., Plusquellec, P., & Taconnat, L. (2020). Benefit of practice of the Stroop test in young and older adults: Pattern of gain and impact of educational level. *Experimental Aging Research*, *46*(1), 52–67. https://doi.org/10.1080/0361073X.2019.1693013

Chein & Morrison, 2010
Chein, J. M., & Morrison, A. B. (2010). Expanding the mind's workspace: Training and transfer effects with a complex working memory span task. *Psychonomic Bulletin & Review*, *17*(2), 193–199. https://doi.org/10.3758/PBR.17.2.193

Cowley & Secchi, 2022
Cowley, S. J., & Secchi, D. (2022). *Organizational cognition: The theory of social organizing*. Routledge.

Davelaar, 2013
Davelaar, E. J. (2013). When the ignored gets bound: Sequential effects in the flanker task. *Frontiers in Psychology*, *3*, 552. https://doi.org/10.3389/fpsyg.2012.00552

Dickenson et al., 2013
Dickenson, J., Berkman, E. T., Arch, J., & Lieberman, M. D. (2013). Neural correlates focused attention during a brief mindfulness induction. *Social Cognitive and Affective Neuroscience*, *8*(1), 40–47. https://doi.org/10.1093/scan/nss030

Dresler et al., 2017
Dresler, M., Shirer, W. R., Konrad, B. N., Müller, N. C., Wagner, I. C., Fernández, G., & Greicius, M. D. (2017). Mnemonic training reshapes brain networks to support superior memory. *Neuron*, *93*(5), 1227–1235. https://doi.org/10.1016/j.neuron.2017.02.003

Evans, Baer & Segerstrom, 2009
Evans, D. R., Baer, R. A., & Segerstrom, S. C. (2009). The effects of mindfulness and self-consciousness on persistence. *Personality and Individual Differences*, *47*(4), 379–382. https://doi.org/10.1016/j.paid.2009.03.026

Gazzaniga, Ivry & Mangun, 2013
Gazzaniga, M. S., Ivry, R., & Mangun, G. R. (2013). *Cognitive Neuroscience: The Biology of the Mind*. Norton.

Gobet & Sala, 2023
Gobet, F., & Sala, G. (2023). Cognitive training: A field in search of a phenomenon. *Perspectives on Psychological Science*, *18*(1), 125–141. https://doi.org/10.1177/17456916221091830

Goel, 2007
Goel, V. (2007). Anatomy of deductive reasoning. *Trends in Cognitive Sciences*, *11*(10), 435–441. https://doi.org/10.1016/j.tics.2007.09.003

Helber, Zook & Immergut, 2012
Helber, C., Zook, N., & Immergut, M. (2012). Meditation in higher education: Does it enhance cognition? *Innovative Higher Education*, *37*(5). https://doi.org/10.1007/s10755-012-9217-0

Hill & Emery, 2013
Hill, P. F., & Emery, L. J. (2013). Episodic future thinking: Contributions from working memory. *Consciousness and Cognition*, *22*(3), 677–683. https://doi.org/10.1016/j.concog.2013.04.002

Hutchins, 1995
Hutchins, E. (1995). *Cognition in the wild*. MIT Press.

James, 2023
James, M. M. (2023). Enacting ontological design: From organism to organization. In D. Secchi, R. Gahrn-Andersen, & S. J. Cowley (Eds.), *Organizational cognition: The theory of social organizing*. Routledge.

Jha, Krompinger & Baime, 2007
Jha, A. P., Krompinger, J., & Baime, M. J. (2007). Mindfulness training modifies subsystems of attention. *Cognitive, Affective, & Behavioral Neuroscience*, *7*(2), 109–119. https://doi.org/10.3758/cabn.7.2.109

Kabat-Zinn, 2015
Kabat-Zinn, J. (2015). Mindfulness. *Mindfulness*, *6*(6), 1481–1483. https://doi.org/10.1007/s12671-015-0456-x

Kirk et al., 2016
Kirk, U., Gu, X., Sharp, C., Hula, A., Fonagy, P., & Montague, P. R. (2016). Mindfulness training increases cooperative decision making in economic exchanges: Evidence from fMRI. *NeuroImage*, *138*, 274–283. https://doi.org/10.1016/j.neuroimage.2016.05.075

Klingberg, 2010
Klingberg, T. (2010). *The overflowing brain: Information overload and the limits of working memory*. Oxford University Press.

Kral et al., 2019
Kral, T. R. A., Imhoff-Smith, T., Dean, D. C., Grupe, D., Adluru, N., Patsenko, E., Mumford, J. A., Goldman, R., Rosenkranz, M. A., & Davidson, R. J. (2019). Mindfulness-based stress reduction-related changes in posterior cingulate resting brain connectivity. *Social Cognitive and Affective Neuroscience*, *14*(7), 777–787. https://doi.org/10.1093/scan/nsz050

Lanzilotti et al., 2022
Lanzilotti, C., Andéol, G., Micheyl, C., & Scannella, S. (2022). Cocktail party training induces increased speech intelligibility and decreased cortical activity in bilateral inferior frontal gyri: A functional near-infrared study. *PLoS One*, *17*(12), e0277801. https://doi.org/10.1371/journal.pone.0277801

Lim et al., 2018
Lim, J., Teng, J., Patanaik, A., Tandi, J., & Massar, S. A. (2018). Dynamic functional connectivity markers of objective trait mindfulness. *NeuroImage*, *176*, 193–202. https://doi.org/10.1016/j.neuroimage.2018.04.056

Miller & Sandford, 2019
Miller, R., & Sandford, R. (2019). Futures literacy: The capacity to diversify conscious human anticipation. In R. Poli (Ed.), *Handbook of Anticipation* (pp. 73–91). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-319-91554-8_77

Miró-Padilla et al., 2019
Miró-Padilla, A., Bueichekú, E., Ventura-Campos, N., Flores-Compañ, M. J., Parcet, M. A., & Ávila, C. (2019). Long-term brain effects of N-back training: An fMRI study. *Brain Imaging and Behavior*, *13*(4), 1115–1127. https://doi.org/10.1007/s11682-018-9925-x

Moore & Malinowski, 2009
Moore, A., & Malinowski, P. (2009). Meditation, mindfulness and cognitive flexibility. *Consciousness and Cognition*, *18*(1), 176–186. https://doi.org/10.1016/j.concog.2008.12.008

Nobre, Tobias & Walker, 2008
Nobre, F. S., Tobias, A. M., & Walker, D. S. (2008). *Organizational and technological implications of cognitive machines: Designing future information management systems*. IGI Global.

Nobre, Tobias & Walker, 2015
Nobre, F. S., Tobias, A. M., & Walker, D. I. (2015). Cognição organizacional: Revisão, conceitualização e contexto estratégico. *Production Journal*, *26*, 742–756.

Paul et al., 2023
Paul, S., Daga, V., Gupta, T., & Aishwarya, A. (2023). A study on the impact of artificial intelligence in small and medium enterprises. *International Journal for Multidisciplinary Research*, *5*(6). https://doi.org/10.36948/ijfmr.2023.v05i06.11145

Posner & Rothbart, 2007
Posner, M. I., & Rothbart, M. K. (2007). *Educating the human brain*. American Psychological Association.

Pozuelos et al., 2019
Pozuelos, J. P., Mead, B. R., Rueda, M. R., & Malinowski, P. (2019). Short-term mindful breath awareness training improves inhibitory control and response monitoring. *Progress in Brain Research*, *244*, 137–163. https://doi.org/10.1016/bs.pbr.2018.10.019

Schacter & Addis, 2007
Schacter, D. L., & Addis, D. R. (2007). The cognitive neuroscience of constructive memory: Remembering the past and imagining the future. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *362*(1481), 773–786. https://doi.org/10.1098/rstb.2007.2087

Schoemaker, 1995
Schoemaker, P. J. H. (1995). Scenario planning: A tool for strategic thinking. *Sloan Management Review*, *36*(2), 25–40.

Secchi & Cowley, 2018
Secchi, D., & Cowley, S. J. (2018). Modeling organizational cognition: The case of impact factor. *Journal of Artificial Societies and Social Simulation*, *21*. https://doi.org/10.18564/jasss.3628

Secchi, Gahrn-Andersen & Cowley, 2022
Secchi, D., Gahrn-Andersen, R., & Cowley, S. J. (2022). *Organizational cognition: The theory of social organizing*. Routledge.

Senior & Butler, 2011
Senior, C., Lee, N., & Butler, M. (2011). PERSPECTIVE–Organizational cognitive neuroscience. *Organization Science*, *22*(3), 804–815. https://doi.org/10.1287/orsc.1100.0532

Simon, 1997
Simon, H. A. (1997). *Administrative behavior: A study of decision-making processes in administrative organizations*. Free Press.

Taren et al., 2015
Taren, A. A., Gianaros, P. J., Greco, C. M., Lindsay, E. K., Fairgrieve, A., Brown, K. W., Rosen, R. K., Ferris, J. L., Julson, E., Marsland, A. L., Bursley, J. K., Ramsburg, J., & Creswell, J. D. (2015). Mindfulness meditation training alters stress-related amygdala resting state functional connectivity: A randomized controlled trial. *Social Cognitive and Affective Neuroscience*, *10*(12), 1758–1768. https://doi.org/10.1093/scan/nsv066

Teece, 2007
Teece, D. J. (2007). Explicating dynamic capabilities: The nature and microfoundations of (sustainable) enterprise performance. *Strategic Management Journal*, *28*(13), 1319–1350. http://www.jstor.org/stable/20141992

Toovey, Kattner & Schubert, 2021
Toovey, B. R. W., Kattner, F., & Schubert, T. (2021). Cross-modal transfer following auditory task-switching training in older adults. *Frontiers in Psychology*, *12*, 615518. https://doi.org/10.3389/fpsyg.2021.615518

Tsoukas & Shepherd, 2004
Tsoukas, H., & Shepherd, J. (2004). Coping with the future: Developing organizational foresight. *Futures*, *36*(2), 137–144. https://doi.org/10.1016/S0016-3287(03)00146-0

Yazici, 2022
Yazıcı, A. (2022). Holographic organizations: Thinking organizations like a brain. *International Journal of Business and Economic Studies*, *4*(2). https://doi.org/10.54821/uiecd.1202495

Weick, 1995
Weick, K. E. (1995). *Sensemaking in organizations*. Sage.

Weiler, Suchan & Daum, 2010
Weiler, J. A., Suchan, B., & Daum, I. (2010). Foreseeing the future: Occurrence probability of imagined future events modulates hippocampal activation. *Hippocampus*, *20*(6), 685–690. https://doi.org/10.1002/hipo.20695

Żołnierczyk-Zreda, Sanderson & Bedyńska, 2016
Żołnierczyk-Zreda, D., Sanderson, M., & Bedyńska, S. (2016). Mindfulness-based stress reduction for managers: A randomized controlled study. *Occupational Medicine (Oxford, England)*, *66*(8), 630–635. https://doi.org/10.1093/occmed/kqw091

SUSTAINABILITY TRANSITIONS AND BACK-CASTING FOR THE ITALIAN FASHION INDUSTRIES

*Marco Bellandi**

1. Introduction

The Italian fashion industries are a powerful and extremely articulated system of systems, spanning different types of territorial and industrial organizations, including a crucial role of industrial districts within larger industrial and urban regions. The study of paths of transitions in this system-of-systems, or in just some of its components, needs to combine structural change with interactive learning and networked agency at the local and trans-local level. This combination implies a non-deterministic and multiple exit view of futures, where back-casting methods and scenario analysis appear to be appropriate for foresight applications.

The paper starts precisely with recalling system-based strategic forecasting and back-casting approaches and their possible application to generating propositions on stepwise support to place-based sustainability transitions, for examples in local productive systems such as industrial districts. Secondly, the paper provides a short assessment on some structural (long-period) features of the Italian fashion industries. Finally, also referring to virtuous international experiences, the final claims of this paper will concern the necessary inclusion, within the priorities of back-casting exercises applied to such industries, of place-based industrial collaborations for the development of sustainability niches and pathways.

It is necessary to point out that this paper does propose neither a specific case study nor a specific back-casting exercise. It is mainly a conceptual paper with an empirical focus (the Italian fashion industries) aiming at suggesting key components that should be included in forward-looking and system-based strategies, such as back-casting, for supporting sustainability transitions in that empirical field.

**Department of Economics and Management, University of Florence, Italy*

2. Sustainability transitions in local productive systems and back-casting

Sustainability transitions point to conditions where an "innovation gap" combines with wicked/disruptive environmental, social, and economic problems and implies quite general processes of radical/systemic innovation and structural change in a socio-technical system (a sectoral or technological field in a territory together with related configurations of markets, industrial, technical, scientific, political and cultural characters), including but not reducing to single innovations on products, materials, technologies, etc. (Geels, 2011). Originally, the concept of sustainability transitions was applied to multi-level functional paths of possible transformation around a new green technology or productive sector. The modelling of such paths pivots on the level of the so-called "regime" that underlies a quasi-stable development of the socio-technical system. The upper level, called "landscape," concerns deep contextual factors, such as international tendencies in institutions, technologies, culture, geo-political and environmental constraints, etc. The lower level, that of "niches," is where potentially disruptive novelties are tried. They may be seen as small worlds shielded from the defensive reactions of the regime, which may join-up, develop and pass selection if meet consistent landscape evolutions, bringing about regime change.

Scholars in regional innovation systems have added, or made explicit, spatial qualifications to the multi-level framework, referring to multi- and cross-territorial spaces that host and are impacted by such processes. The multi-level structure of the transition (landscape; sociotechnical regime; niche emergence, experiments, and selection; and regime transformation) can be referred to the interplay between different Techno-Industrial Spatial Systems of Specialization (TISSSs) and footless systems (De Propris & Bailey, 2021):

a) The regime: the core solutions that are dominant in certain fields of technological or industrial specialization can be led either by some TISSSs, following paths of quasi-steady development, or by the strategies of footless multinational companies and platforms managing productive sites around the world.

b) The niches: some TISSs feature or host secondary or peripheral sectors within or without their sectors of specialization, where local incubation of possibly disrupting novelties may operate; non-strictly place-based expressions of contexts hosting niches may be international networks of community of practices and footless innovative startups.
c) The landscape: general institutions, broad tendencies and challenges, and national, trans-national, sectoral, and technological innovation systems, either support the regime or open windows of opportunity for niches.

The TISS is a form of Local Productive System (LPS), i.e., a local system (an area of interrelated municipalities or a small region) characterized by productive specializations showing a local division of labor, embedding in the local socio-cultural and institutional context, and open to wide (national and international) trade and production networks, value chains, and markets. They may be centered either on the activity of large firms that anchor locally or on clusters of SMEs (the case of the industrial districts), or in some combinations of the two (Bellandi & De Propris, 2021). They express a logic of industrial organization and territorial development alternative to that based on footless productive investments by large multinational companies and platforms backed by global financial capital or sovereign funds. TISSs where large firms do not dominate can be seen as the regular context for niches (Sahimaa et al., 2023).

TISSSs are strong LPSs leading the technologies of a regime or hosting niches for a new regime. Their technological and innovation capabilities relate also to innovation systems, at regional, national, international and sectoral level, where actors intersect the local business and socio-cultural life with interactive learning in some specific fields. LPSs include, as well, cases that are less developed in terms of intersections with innovation systems of different types. They, however, can be important in processes of docking and diffusion of emergent niches.

According to a quite long stream of literature on local development and industrial districts, the phases of transition in LPSs are characterized not only by the multiplicity of possible paths (bifurcations), but also by a collective difficulty to understand the options and their feasibility, as well as by uncoordi-

nated individual attempts to try different solutions or to defend the status quo, with consequential conflicts and risks of lock-ins (Belussi, 2009). Lock-in would mean just to stick to "business as usual," which however may also bring about a worsening with respect to the status quo, till the decline of the LPS as such.

The presence of place-leaderships (and policymakers within them), open to transformation and sustainability outcomes, is acknowledged to be an important lever against lock-in. The literature associates to them the capability to figure out a vision of change, share it and develop feasible scenarios and policies with the involvement and active participation of all the crucial types of stakeholders of the community (Sotarauta, 2017).

This type of capability and the associated initiatives are precisely the requisites for strategic foresight (Corazza et al., *infra*) applied to innovation systems and their overlaps with socio-technical systems and LPSs (Anderson & Anderson, 2014). On the other side, the knowledge of the codified methodologies of strategic foresight and the awareness about the possibility of their use at the local and regional levels can be an important tool in the hand of place-leaderships to strengthen the possibilities of sustainability transition. We will come back to this in Section 4.

3. Italian fashion industries and European cases of evolving fashion industries

Made in Italy is an evolving and complex concept (Belfanti, 2019; Dellapiana, 2022).[1] Fashion, pivoting on textile, clothing, and leather sectors, is one of the cores of made in Italy (Fortis & Carminati, 2009).

Fashion industries play a significant role in many Italian regions. These specializations, their markets, and their industrial and territorial organization have evolved over the last decades. One remarkable trend, which explains the peculiar capability to keep these seemingly traditional and low-tech specializations within a high-income country against the increasing competition of new industrializing countries, concerns the increasing cultural, creative, and quality contents of the Italian productions (Arrighetti et al., 2024).

The evolution of the industrial and territorial organization in the last decades builds on some quite invariant structural features, including the presence in north-center Italy both of some large manufacturing firms with strong anchors in LPSs (e.g., the Miroglio Group in Piedmont) and of industrial districts and other types of LPSs hosting strong industrial clusters driven by SMEs (Becattini, 1998). This multiple industrial-territorial basis has faced international competition and thrived against the great challenges of the last 15 years, thanks to processes of selection, which surely have reduced local employment, increased investments in global value chains, and enhanced flexibility and versatility (Foresti & Giusti, 2022).

Three other interconnected features contribute to such resilience. They are the spin-out of luxury international brands from a tradition in high-couture, the vast differentiation of the fabric of high added value fashion services from the first catwalks and dressmakers in the 1960s, and the concentration of both the Italian international brands' headquarters and the most powerful clusters of fashion services in some regional capital cities. Indeed, a large part of the industrial districts with fashion specializations in north-center Italy forms sort of rings around Italian cities such as Milan, Florence and Padova & Venetia, which, with their huge cultural and artistic heritage and the concentration of cultural and creative industries, represent crucial pivots in the elaboration of images and contents of Made in Italy (Dunford, 2009). Of course, the representation of such functions could be extended also to parts of center-south regions and isles of Italy, for examples around Naples and Bari.

The high added value fashion services include or overlap with (Bettiol & Micelli, 2005): a) secondary and vocational schools and higher education institutions providing the basis for the specialized human capital, together with university R&D, technological transfer, and market, design and cultural research activities performed in collaboration with the business sector; b) think-tanks for the elaboration and monitoring of specialized public policies; c) initiatives by civic organizations and communities of experts, which help the relations of the fashion industry with the cultural heritage of the places involved, and now also with the growing sensibility of consumers and citizens with the needs and principles of sustainability.

The Italian fashion industries are a global powerhouse. However, the dramatic challenges of the last period are not without risks. We focus here, specifically, on the challenge represented by the growing unsustainability of the world-wide fashion regime. According to Buchel et al. (2022, p. 231), this is "locked into a state of disconnection, uncontrollability, extraction, growth-focus, and disposability," overproduction and overconsumption being at its core, resulting in an increasing "clothing mountain" (p. 235). Indeed, the step consolidating this heavily extractive regime was the success of mass low-medium quality fast fashion, pioneered by Benetton in the 1980s, then superseded by Zara and H&M, and now by the exponential growth of that quintessential expression which is hyper-fast fashion by e-commerce platforms and fleets of large aircrafts circulating daily to take mountains of low price and very low-quality and shortest longevity items around the world.[2]

Presently, the Italian fashion industries navigate between the linear global fashion regime and niches of more circular and sustainable solutions. Consider the international high quality fashion dressmakers, taking to the development of large luxury brands, many of them now controlled by huge French luxury groups. Large luxury brands are involved, with some of their lines of business, in the development of sustainable solutions. They might be important for the transition to a new regime given the vast economic and strategic resources they control. However, left alone, it is quite probable that sustainable solutions of the large luxury brands would be often partial and "superficial" (Sahimaa et al., 2023). Signs of this "superficiality" have been found in the production of some luxury fashion by sweatshops in the Milan hinterlands.[3]

What about the other pillar of Italian leadership in fashion? It is the "magic circle" (Dunford, 2009) of LPSs specialized in fashion industries with complementary industries of accessories and machinery and the fashion service clusters in fashion capitals. Their business populations have grown with linear business models typical of made in Italy, combining a good quality in terms of design and functionality with increasing personalization on international segments of differentiated markets. Some of these LPSs present traditions of partial circularity, like the carded wool coming from recycling of rags in the textile dis-

trict of Prato, and develop collective green certificates in production processes, such as district Ecolabels (Bellandi et al., 2021).

In general, the competitive positioning of such magic circle outside mass production and mass marketing and their embeddedness in the laboratory of life experiences of local communities might help them to play an important role for expanding niches and pathways to sustainability in fashion. It could be even argued that this is not just a possibility but, more, a necessity, being the only field where this magic circle might find spaces of competitive advantage in the future. However, the perspective implies not just single innovations and technological progresses, but a systemic change that has the true nature of sustainability transitions. Next section looks at this change under the lens of strategies of future and place-based back-casting frameworks (Bellandi & Stark, 2025).

4. Back-casting sustainability transitions in Italian fashion industries

We know that the landscape in which the global fashion system moves is nowadays characterized by contradictory forces (e.g., see "consumerist fashion"). The linear extractive model of the dominant regime in the fashion industries and systems worldwide is an expression of growth-at-all costs, i.e., precisely, the growth of economic power and material consumption. The push towards regime-change is supported by public and private bodies, new technologies (green and digital), and growing ethical concerns in segments of consumers and entrepreneurs in face of the global pressure of environmental and societal challenges. Various types of niches have been emerging worldwide in support of regime-change towards circularity and longevity in doing and using fashion products.

According to Buchel et al. (2022, pp. 236-238), four types of fields of such niches may be recalled: 1) practices of sourcing of recycled safe textile fibers and energy saving solutions in production processes; 2) longevity and sufficiency of products in a perspective of fashion as a long-term personalized service to customers; 3) transparency and control for the application of

ethical principles in the employment of workers; 4) consumer activism for advocacy of a sufficiency culture and for learning and doing on slow fashion.

Can the magic circle of the Italian fashion industries liaise with such types of niches, being both a context for their development and diffusion and a prime beneficiary of a related regime-change? Of course, the question is too broad to be discussed here. However, it is possible to draw, both from the previous discussion in Section 2 and from international cases, some general considerations on key features of strategies of futures and place-based back-casting that could support such outcomes, focusing on the context of change in a single LPS contributing to the magic circle (Bellandi & Stark, 2025).

We put these considerations within the synthetic list that follows.

- Vision setting and baseline – industrial core: Given the strength of the regime of the linear extractive regime in the fashion industries and systems, led today and symbolized by hyper fast fashion, what are the real factors of strength and weakness for growing specific niches pointing to a new regime of sufficiency, circular, slow fashion? This should be considered in a preliminary SWOT analysis of the background and in relation to what learning and monitoring can be developed along the pathways (Le Feber & Smit, 2023);
- Vision setting and baseline – local system: The seeds and prospects of a systemic solution for sustainability need to be identified within the context of a specialized business cluster but their development might take protection and traction from inclusion in the broader context of a shared vision of sustainability by the local civic and business community (UN-SDSN, 2015), even if this adds complexity (Vergragt & Quist, 2011);
- Prioritization: Place-based industrial collaborations on sustainable niches are fundamental, together with social innovation for tying transition to the well-being of families and community;
- Key initiatives: a) combinations of manufacturing and knowledge intensive services such as digital based services

extending material performances of textiles and apparels; b) the brokering of cross-sectoral innovation at the local level or at cross-local and multi territorial levels, e.g., for interaction of fashion clusters with clusters hosting high-tech niches for sustainability; c) the engagement of universities and public research organizations, with their knowledge for the common good and control of different disciplinary bases of knowledge (Bellandi & Santini, 2020).

5. Conclusions

Industrial districts and other types of LPSs and clusters in the magic circle of Italian fashion industries have thrived, in the past century, thanks to the embeddedness of rich fabrics of small entrepreneurs, some growing big, in the life of the territory and the community (Becattini, 2015). The extension of these collective ties to support sustainability transition in a perspective of regime change, away from linear extractive models, is more than a hypothetical possibility.

Methods of strategic foresight and back-casting founded on a comprehensive understanding of not only technological opportunities but also of complex and conflictual socio-technical and territorial systems might support such sustainability transitions.

Policies for circular textiles, such as those in the making by the EU (EUC, 2022), might enter sustainability transitions positively, but policies can have positive effects if they are consistent with futures that are not only better but also feasible along pathways of seed innovation, niche development, and regime change (EMF, 2021).

Notes

[1] Lot of study is devoted to this fuzzy concept also within MICS (www.mics.tech/).

[2] Il Sole 24ore, March 15, 2024: Chiara Beghelli, Shein punta sull'Italia e i suoi designers.

[3] Il Sole 24ore, June 30, 2024: Ivan Cimmarusti, Sara Monaci, Moda e caporalato. For a different approach: Il Sole24 ore, 2024, July 7: Giulia Crivelli, Cucinelli alle imprese di Firenze la moda si salva tutelando l'artigianalità.

References

Andersen & Andersen, 2014
Andersen, A. D., & Andersen, P. D. (2014). Innovation system foresight. *Technological Forecasting and Social Change*, *88*, 276–286. https://doi.org/10.1016/j.techfore.2014.06.016.

Arrighetti, de Nardis & Traù, 2024
Arrighetti, A., de Nardis, S., & Traù, F. (2024). *Il falso mito della manifattura inefficiente*. Luiss – Institute for European Analysis and Policy. Working paper 11/2024. https://leap.luiss.it/wp-content/uploads/2024/07/WP11.24-Il-falso-mito-della-manifattura-inefficiente.pdf

Becattini, 1998
Becattini, G. (1998). *Distretti industriali e Made in Italy. Le basi socioculturali del nostro sviluppo economico*. Bollati Boringhieri.

Becattini, 2015
Becattini, G. (2015). Beyond geo-sectoriality: The productive chorality of places. *Investigaciones Regionales*, *32*, 31–41. https://EconPapers.repec.org/RePEc:ris:invreg:0291

Belfanti, 2019
Belfanti, C. M. (2019). *Storia culturale del Made in Italy*. Il Mulino.

Bellandi & De Propris, 2021
Bellandi, M., & De Propris, L. (2021). Local productive systems' transitions to Industry 4.0. *Sustainability*, *13*, 13052, 1–17. https://doi.org/10.3390/su132313052

Bellandi & Santini, 2020
Bellandi, M. & Santini, E. (2020). Place leadership in emerging product-service systems. *International Journal of Business Environment (IJBE)*, *11*(3), 321–335. http://dx.doi.org/10.1504/IJBE.2020.110902

Bellandi & Stark, 2025
Bellandi, M. & Stark, E. (2025). SME clusters as the driving force behind the popularisation of slow fashion. *European Planning Studies*, print-on-line. https://doi.org/10.1080/09654313.2025.2524000

Bellandi, Ruiz-Fuensanta & Santini, 2021
Bellandi, M., Ruiz-Fuensanta, M. J., & Santini, E. (2021). Factors of environmental sustainability in Italian industrial districts: A composite environmental sustainability index. In S. R. Sedita & S. Blasi (Eds.), *Rethinking Clusters. Sustainable Development Goals Series* (pp. 111–124). Springer. https://doi.org/10.1007/978-3-030-61923-7_9

Belussi, 2009
Belussi, F. (2009). Knowledge dynamics in the evolution of Italian industrial districts. In G. Becattini, M. Bellandi, & L. De Propris (Eds.), *A Handbook of Industrial District* (pp. 457–470). Edward Elgar.

Bettiol & Micelli, 2005
Bettiol, M. & Micelli, S. (Eds.) (2005). *Design e creatività nel made in Italy. Proposte per i distretti industriali*. Bruno Mondadori.

Buchel et al., 2022
Buchel, S., Hebinck, A., Lavanga, M., & Loorbach, D. (2022). Disrupting the status quo: A sustainability transitions analysis of the fashion system. *Sustainability: Science, Practice and Policy*, *18*(1), 231–246. https://doi.org/10.1080/15487733.2022.2040231

Dellapiana, 2022
Dellapiana, E. (2022). *Il design e l'invenzione del Made in Italy*. Einaudi.

De Propris & Bailey, 2021
De Propris, L., & Bailey, D. (2021). Pathways of regional transformation and Industry 4.0. *Regional Studies*, *55*(10–11), 1617–1629. https://doi.org/10.1080/00343404.2021.1960962

Dunford, 2006
Dunford, M. (2006), Industrial districts, magic circles, and the restructuring of the italian textiles and clothing chain. *Economic Geography*, *82*, 27–59. https://doi.org/10.1111/j.1944-8287.2006.tb00287.x

EMF, 2021
EMF (2021). *Circular business models: Redefining growth for a thriving fashion industry*. Ellen MacArthur Foundation. https://ellenmacarthurfoundation.org/fashion-business-models/overview

EUC, 2022
EUC. (2022), *EU strategy for sustainable and circular textiles, EU Commission*. COM 2022, 141 final, Bruxelles. https://environment.ec.europa.eu/document/download/74126c90-5cbf-46d0-ab6b-60878644b395_en?filename=COM_2022_141_1_EN_ACT_part1_v8.pdf

Geels, 2011
Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, *1*(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002Get rights and content

Foresti & Giusti, 2022
Foresti, G. & Giusti, S. (2022). Le filiere produttive nei distretti industriali lette attraverso i flussi di pagamento tra imprese. *Scienze Regionali*, *3*. https://www.rivisteweb.it/doi/10.14650/102499

Fortis & Carminati, 2009
Fortis, M. & Carminati, M. (2009). Sectors of excellence in the Italian industrial districts. In G. Becattini, M. Bellandi, & L. De Propris (Eds.), *A Handbook of Industrial District* (pp. 417–428). Edward Elgar.

Le Feber & Smit, 2023
Le Feber, N., & Smit, M. J. (2023). Fashion companies pioneering with eco-innovations in the Swedish fashion industry: Motivations, resources, and co-operation. *Circular Economy and Sustainability*, *3*, 1885–1905. https://doi.org/10.1007/s43615-022-00246-x

Sahimaa et al., 2023
Sahimaa, O., Miller, E. M., Halme, Niinimäki, M. (2023). From simplistic to systemic sustainability in the textile and fashion industry. *Circular Economy and Sustainability*, *4*(2), 1–17. https://doi.org/10.1007/s43615-023-00322-w

Sotarauta, Beer & Gibney, 2017
Sotarauta, M., Beer, A., & Gibney, J. (2017). Making sense of leadership in urban and regional development. *Regional Studies*, *51*(2), 187–193. https://doi.org/10.1080/00343404.2016.1267340

UN SDSN, 2015
UN SDSN. (2015). *United Nations sustainable development solution network getting started with the sustainable development goals. A guide for stakeholders*. Chapter 3. Medium. https://sdg.guide/

Vergragt & Quist, 2011
Vergragt, P-J., & Quist, J. (2011). Backcasting for sustainability: Introduction to the special issue. *Technological Forecasting and Social Change*, *78*(5), 747–755. https://doi.org/10.1016/j.techfore.2011.03.010

FUTURE-PACK. TOWARD A TAXONOMY OF SMART SOLUTIONS FOR ADVANCED PACKAGING DESIGN

Erik Ciravegna, Silvia Barbero**, Davide Pletto*, Mariapaola Puglielli**, Martina Spinelli***

1. Introduction

Packaging is a complex artifact (Ciravegna, 2010; 2017) that, beyond its nature as an object of use, is a powerful means of communication capable of conveying not only product qualities and brand values but also relevant information concerning the entire sector in which it is inserted, thus constituting a mediating element, a key point of contact between actors in the supply chain and between them and the end-users. Moreover, thanks to digital technology, packaging has transformed over time into a truly "smart device" that can track the supply chain, check the integrity and safety of goods, and potentially record the entire history of each product and its impacts.

The convergence of megatrends such as sustainability and digitalization (Lichtenthaler, 2021), particularly the rise of e-commerce, has sparked a profound transformation in the packaging industry. The growing emphasis on the circular economy (European Commission, 2020; Kirchherr et al., 2017), coupled with stricter regulations on packaging waste—such as the so-called "Packaging and Packaging Waste Regulation" (PPWR) (European Commission, 2022)—and heightened consumer awareness of sustainability issues (Bar Am et al., 2023), is compelling companies to re-evaluate their products and processes to minimize environmental impact and enhance overall value (Marrone & Raimo, 2021). Simultaneously, technological advancements, including the proliferation of digital devices and social media platforms, alongside the rapid shift towards online shopping accelerated by the COVID-19 pandemic (LaBerge et al., 2020), present both significant challenges and transformative opportunities for sustainable manufacturing and business practices (Moghrabi et al., 2023).

Within the context of the MICS extended partnership's re-

**Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

***Department of Architecture and Design, Politecnico di Torino, Italy*

search activities, the study *FuturE-Pack: Digital Advanced Design for the Enhancement of Packaging as a 'Broadcaster' in the Made in Italy Supply Chain* (Project 1.1) investigates the utilization of digital solutions to augment packaging functionality as a communication tool within Made in Italy sectors. This research, conducted by a collaborative team from the University of Bologna, the University of Florence, and the Polytechnic University of Turin, examines how digital technology can transform packaging into an intelligent device capable of tracking and monitoring product integrity and safety throughout the supply chain. A digitally enhanced container also has the potential to record comprehensive product histories and associated environmental impacts, all while effectively communicating brand identity and values.

The project "FuturE-Pack" aims to develop a portfolio of digitally advanced solutions to enhance the role of packaging as both a mediator and a communication medium ("broadcaster") within the supply chain. These solutions will facilitate the recording, archiving, and disseminating of product-related information (e.g., sustainability metrics, brand identity) by simplifying and translating complex data into formats accessible to various stakeholders. The primary objectives are twofold. First, to equip stakeholders in the Made in Italy supply chain with digital tools that streamline information exchange, thereby promoting the safe, cost-effective, and efficient handling of goods, and contributing to the development of sustainable (*green*) logistics practices. Second, to enhance the end-user experience by providing transparent, accessible, and inclusive product information, including details about their impacts, according to the three pillars of sustainability (Purvis et al., 2019): *planet* (environmental), *people* (social), and *profit* (economic). This will also enable clearer communication of territorial and brand identity, along with associated tangible and intangible values, particularly for luxury brands.

The initial phase of this research focused on mapping and analyzing the current state of the art by collecting relevant case studies of existing and potential digital solutions for packaging, along with their functionalities. Additionally, a comprehensive review of the scientific literature about life cycle assessment and product impact analysis was conducted. Future research will analyze the supply chain and stakeholder ecosystem related



1. Conceptual framework and structuring of the project.
All images are reproduced in color in the online edition of the book.

to packaged goods, especially within the e-commerce and fashion industry (A1 sector), which are the primary areas of analysis and experimentation for this project (fig. 1).

This essay focuses on the initial phase of research, presenting the work conducted on the collection, cataloging, and analysis of case studies. This analysis resulted in the development of a taxonomy of smart solutions that can be integrated into advanced packaging design to address the significant contemporary challenges of sustainability and circularity.

2. Smart packaging: Utilized technologies and applications

Originally intended as a simple containment element, packaging has evolved into an integral part of product design, serving not only to contain but also to protect and preserve (Lydekaityte & Tambo, 2020). However, this traditional view of packaging is undergoing a paradigm shift due to the increasing complexity of products and rising consumer expectations. Moreover, packaging is now recognized as a vital facilitator of the transition to a circular economy, encompassing functionalities such as life cycle assessment, product life extension, and a more sustainable supply chain. This transformation is further driven by the rapid development of digital technologies, such as the Internet of Things, biopolymers, and nanomaterials (Schaefer & Cheung, 2018; Palazzo et al., 2023). In light of these developments, the term *packaging* alone is no longer adequate to describe the current state of the art. The focus is now shifting from the basic concept of packaging to the more advanced concept of *smart packaging*.



2. Main packaging functions for each type of smart packaging. Adapted from Lydekaityte & Tambo, 2020.

Smart packaging refers to any packaging that incorporates advanced technologies to enhance its primary functions or introduce new functionalities going beyond those of conventional packaging. Brockgreitens and Abbas (2016) define smart packaging as incorporating advanced technologies for the purpose of achieving these goals. As Nandanwade Priyanka & Nathe Parag (2013) explain, the functionality of smart packaging goes beyond merely improving essential functions. It can also respond to stimuli emanating from the packaged product or its surrounding environment, thereby ensuring efficient preservation, protection, facilitating convenience, and enabling communication between various stakeholders in the supply chain, including consumers. The technologies used in smart packaging can be chemical, electrical, electronic, mechanical, or digital network-connected in nature, or a combination of these. Packaging can be categorized into three main types (fig. 2) based on their primary function, the type of technology used, and their interaction with both the content and the users: *active packaging*, *intelligent packaging*, and *interactive packaging* (Lydekaityte & Tambo, 2020; De Kruijf et al., 2002; Ozcan, 2020).

Active Packaging: This type of packaging interacts directly with the product to improve its quality and shelf life. It creates and maintains an optimal internal environment through mechanisms such as absorption (removal of unwanted substances) or release (supply of beneficial compounds).

Intelligent Packaging: Incorporating systems capable of sensing, tracking, and communicating information, intelligent packaging aims to facilitate decision-making, extend shelf life, and improve product safety and quality. Unlike active packaging, it monitors and provides information without directly altering the product. It contains hardware components such as indicators (for time-temperature, freshness, and integrity), sensors (including biosensors, gas sensors, and thermochromic inks), RFID systems, and innovative tags (e.g., QR codes, NFC, WebAR codes, and digital watermarks) that provide additional information when scanned.

Interactive Packaging: This type of packaging actively engages the consumer through design or technology, enhancing their experience and interaction with the product or its functionality. It leverages advances in printed electronics, augmented reality,



3. Preliminary taxonomy of the main technologies used in smart packaging.

IoT, and NFC—along with standardized communication protocols—to create a more dynamic user experience. As Nilsson et al. (2012) noted, interactive packaging can enable digital services that are accessible via the internet, which significally expands design possibilities and application potential, especially through the integration of IoT technologies.

Preliminary research on smart packaging led to an initial taxonomy of technologies used in this field, encompassing *sensors*, *indicators*, *data carriers*, *emitters*, *preservative releasers*, and *other active and interactive systems* (fig. 3). This preliminary taxonomy was developed to facilitate the efficient collection, categorization, and subsequent analysis of case studies. In line with the project's objectives, elements related to active packaging were excluded, limiting the focus to case studies involving intelligent and interactive packaging (i.e., those utilizing digital technologies).

This taxonomy enabled the systematic collection and analysis of some relevant case studies, particularly those focusing on digital solutions for product labeling, tracking, and tracing. A preliminary analysis of these case studies is presented below.

Tab. 1. Preliminary collection and analysis of case studies.

#	Project Name	Type	Description	Country	Reference Link
1	The Lime Loop	Temperature Sensor, Motion Sensor, Geolocation, Packaging	Reusable packaging allows for real-time tracking of dispatched parcels and can be returned for further use after delivery	United States	https://thelimeloopshop.com/
2	Living Packets	Motion Sensor, Temperature and Humidity Sensor, Geolocation, Integrity Indicator	This sturdy, reusable box made from expanded polypropylene features a code-activated closure, ensuring secure delivery. Real-time tracking is available, and the box can be reused for future shipments	France	https://livingpackets.com
3	Flagship Tracker	Motion Sensor, Temperature and Humidity Sensor, Geolocation, Integrity Indicator	A device placed inside parcels for shipping large items. It monitors various parameters during transit, including location, temperature, humidity, impacts, and product orientation	Australia, India, Germany, USA	https://globalcoldchain.com/en/product/flagship-tracker/

4	R Collective and Avery Dennison	QR Code	Avery Dennison, collaborating with The R Collective and Levi's, introduced eco-friendly labels with QR codes for their "Denim Reimagined" collection. These labels offer consumers access to garment information and sustainability messages	Worldwide	https://apparelsolutions.averydennison.com/
5	Sheep inc	NFC	An NFC-enabled label attached to wool textiles allows customers to virtually experience the origin of the wool in New Zealand	New Zealand	https://eu.sheepinc.com/
6	Trimco Group	Motion Sensor, Temperature and Humidity Sensor, Geolocation, Integrity Indicator	Trimco Group specializes in RFID technology for branding and supply chain traceability. Their RFID tags and labels enable tracking of individual products from production to point-of-sale and beyond, enhancing data reliability and inventory management	France	https://www.trimco-group.com/
7	Atma.io.	Motion Sensor, Temperature and Humidity Sensor, Geolocation, Integrity Indicator	This platform assigns unique digital IDs to products, enabling end-to-end transparency by tracking and managing every event throughout a product's lifecycle, from source to consumer and beyond, promoting circularity	France	https://www.atma.io/

3. A taxonomy of smart solutions for advanced packaging design

The investigation of the different smart packaging types and the initial analysis of case studies provided crucial insights for developing a comprehensive overview of existing digital solutions as an essential conceptual framework for the project. The preliminary exploration led to the creation of a standardized data collection and classification system, which facilitated the development of a more detailed taxonomy of technologies currently employed in packaging. This framework, in turn, served as the basis for the creation of an expanded catalog of case studies.

Following the methodology of the Packaging Innovation Observatory (Ciravegna, Pletto, & Pasini, 2024; Giardina, 2024), the research process involved the investigation, mapping, interpretation, and collection of sector innovations. This was achieved through a design-driven approach, integrating knowledge and expertise from different scientific and technological disciplines. Additionally, relevant documentation, including scientific publications, technical reports, and media related to packaging design, was analyzed to identify current trends.

The monitoring process covered not only packaging solutions but also digital technologies, logistics solutions, and communication projects. While not exhaustive, the case studies on digitally enhanced packaging provide valuable insights into the innovative dynamics at play. To expand the sample and gain a more comprehensive perspective, case studies from the fashion sector that were not directly related to packaging solutions were also included in the analysis. These case studies focused on labels and accessories, identified as key elements among the analyzed products.

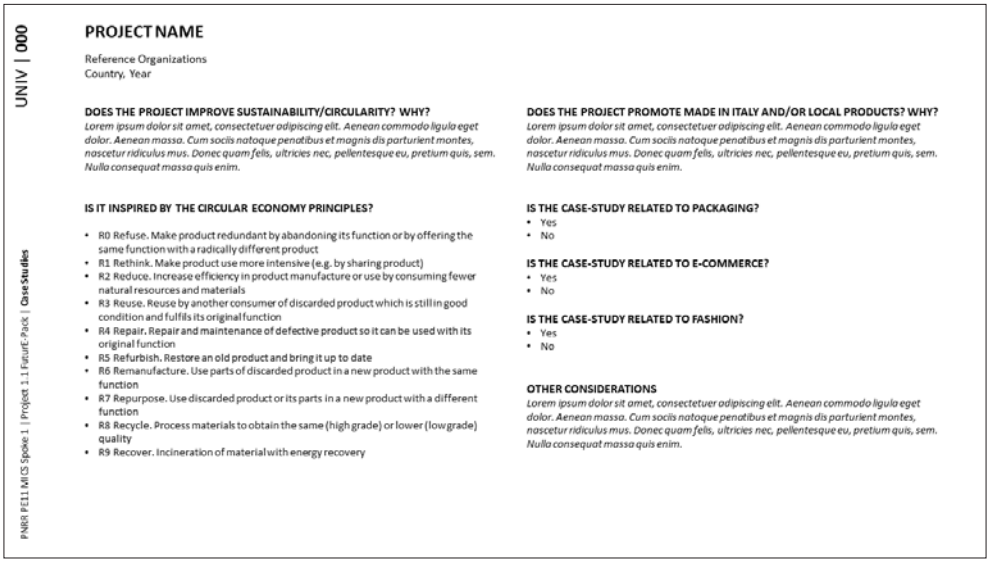
To ensure consistency in the collection and analysis of projects across the three partners, a unified filing system, incorporating a standardized case study template, was developed based on shared criteria. The template includes elements such as the digital systems and technologies employed to perform specific functions, the relationship (direct or indirect) with the promotion of Made in Italy or local products, and the principles of the circular economy addressed in each case study.

The case study template is structured into three main sections. The first section (fig. 4) provides a comprehensive overview of the basic information of the project, including a description, details of any awards and patents, and additional resources for further exploration of the case study.

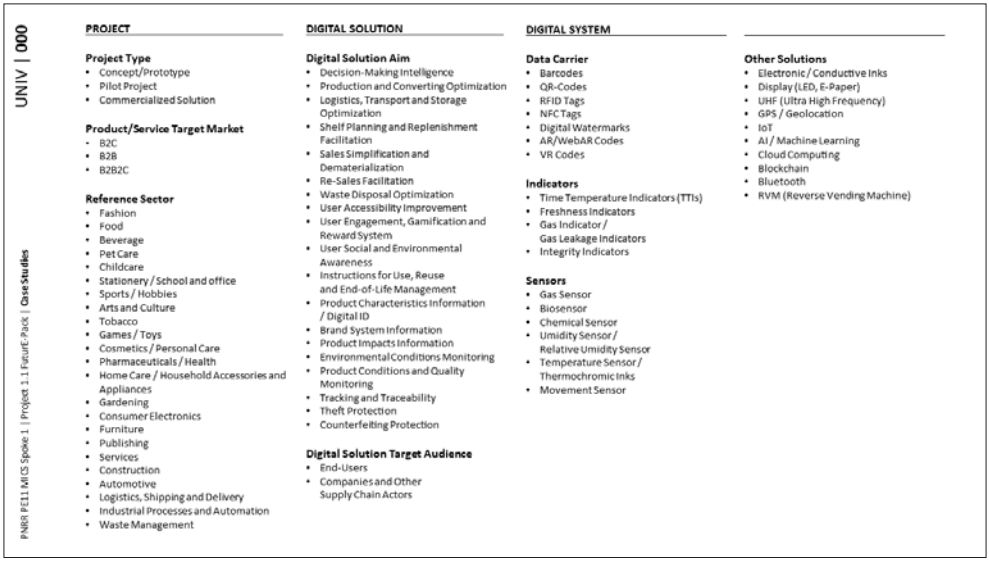
The second section of the case study template analyzes the project's connection to the project's key themes. It is divided into two parts: the first provides an overview of the case study's sustainability aspects, emphasizing the so-called *9Rs* of the circular economy (Ellen MacArthur Foundation, n.d.); the second examines how Made in Italy is promoted and whether the case study directly relates to packaging, e-commerce channel, or fashion industry.



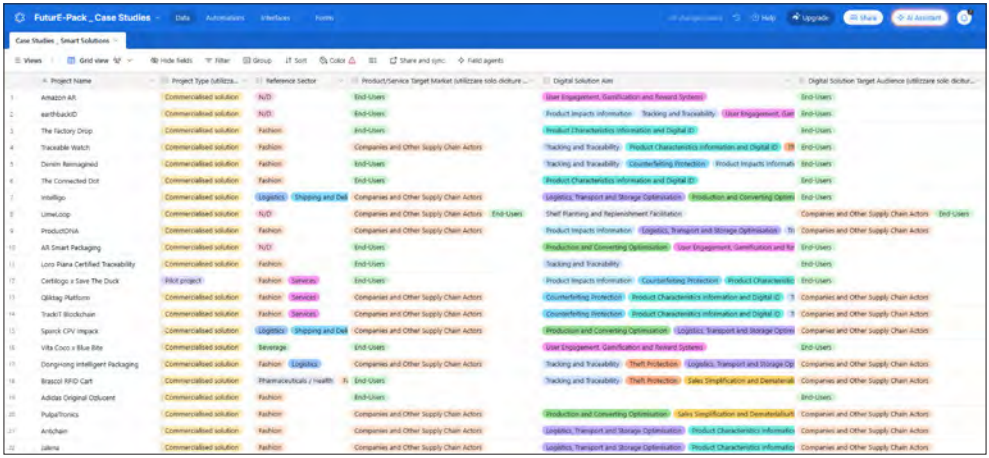
4. Initial section of the case study template for the filing system.



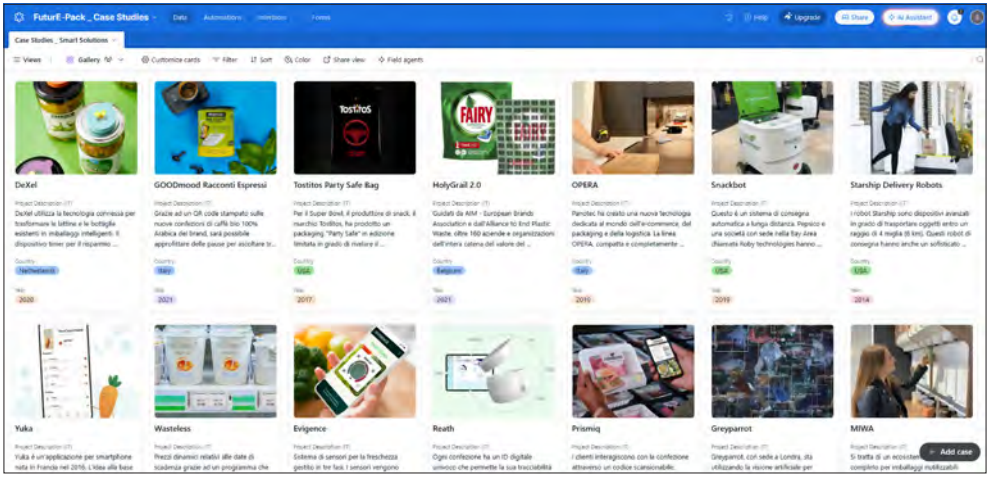
5. Second section of the case study template for the filing system.



6. Third and final section of the case study template for the filing system.



7. Screenshot of the grid view of the online database (AirTable).



8. Screenshot of the gallery of the online database (AirTable).



9. Totality of the case studied collected and analyzed so far.

The third section provides a comprehensive overview of the digital system central to the case study. It clarifies the system's objective and underlying technological solutions and components. Additionally, it specifies the type of project analyzed, the target market, and the reference product sector.

The collected case studies were organized within an online database (*AirTable*), enabling modular and dynamic data structuring for enhanced management and exploration (figs. 7-8). Cases were also tagged to highlight their innovative aspects and value drivers, which are the key factors contributing to value creation within the project.

The approach prioritizes objective and quantifiable data while incorporating qualitative and narrative elements for a multidimensional analysis, utilizing conceptual grids and tools tailored to the specific analytical needs. The collection process yielded 185 case studies, categorized as follows: 122 related to packaging, 53 to fashion, 55 to e-commerce, 26 to products associated with Made in Italy or local territories, and 64 to environmental sustainability and circularity. These cases were cataloged and underwent in-depth analysis using a research team-developed taxonomy, enabling detailed classification and a deeper understanding of the variables involved.

In-depth analysis and systematization of the case studies resulted in an updated and expanded taxonomy of smart packag-

ing solutions, organized by digital system. Each system includes a reference technology and several subcategories (numbers in parentheses denote distinct typologies within each technology):

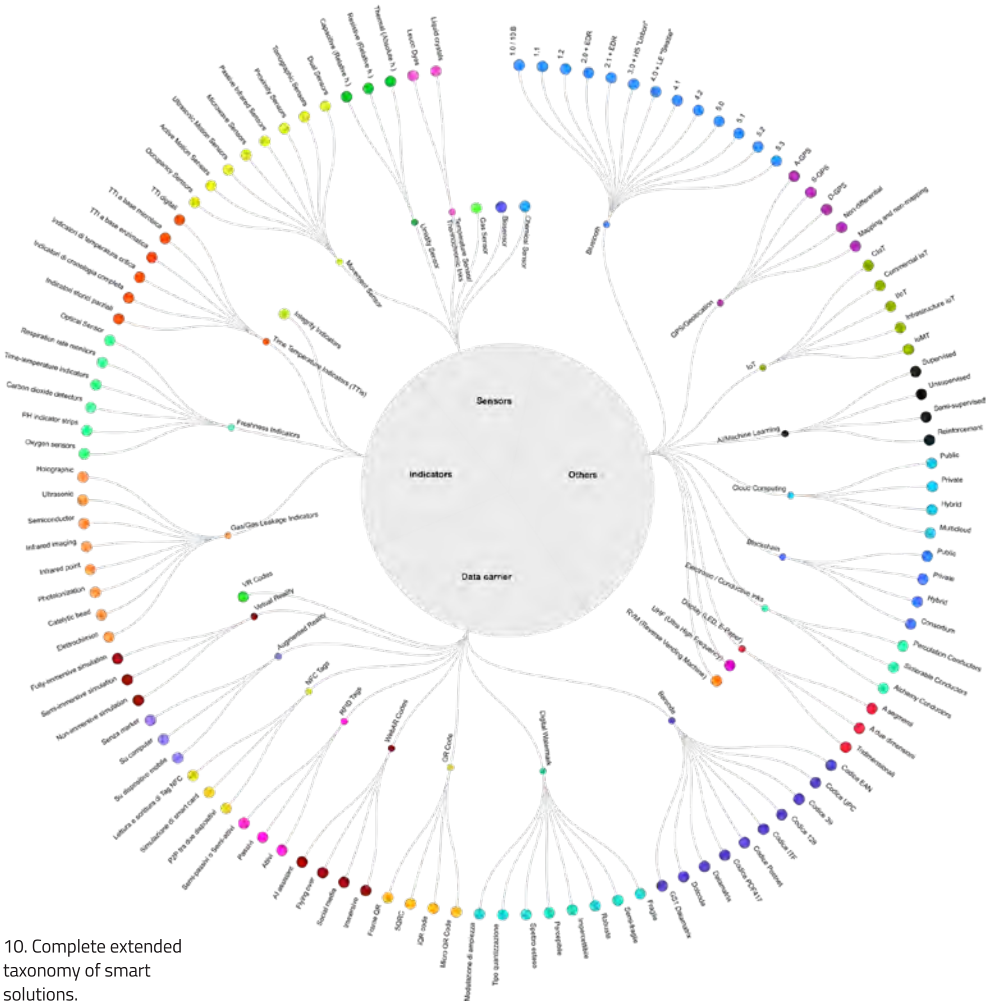
- *Data Carriers*: Barcodes (12); QR-Codes (44); RFID Tags (20); NFC Tags (41); Digital Watermarks (7); AR/WebAR Codes (13); VR Codes (4);
- *Indicators*: Freshness Indicators (12); Gas and Gas Leakage Indicators (1); Integrity Indicators (7); Time Temperature Indicators (7);
- *Sensors*: Gas Sensor (1); Biosensor (2); Chemical Sensor (5); Humidity Sensor (4); Movement Sensor (10); Temperature Sensor / Thermochromic Ink (13);
- *Other Solutions*: Electronic / Conductive Ink (1); Display (LED, E-Paper) (4); UHF (2); GPS / Geolocation (8); RVM (3); Cloud Computing (14); AI / Machine Learning (20); Bluetooth (1); Blockchain (15); IoT (12).

The details of all categories and subcategories are shown in figure 10.

In addition, in response to the requirements identified during case study selection, a *digital solution aims* list was defined, describing the needs and requirements that the solutions aim to satisfy: Decision-Making Intelligence; Logistics, Transport, and Storage Optimization; Shelf Planning and Replenishment Facilitation; Re-Sales Facilitation; Production and Converting Optimization; Sales Simplification and Dematerialization; Waste Disposal Optimization; User Accessibility Improvement; User Engagement, Gamification/Reward System; User Social and Environmental Awareness; Instructions for Use, Reuse, and End-of-Life Management; Product Characteristics Information/Digital ID; Brand System Information; Product Impacts Information; Environmental Conditions Monitoring; Product Conditions and Quality Monitoring; Tracking and Traceability; Theft Protection; Counterfeiting Protection.

4. Conclusions

The integration of smart solutions into advanced packaging presents both significant opportunities and challenges across



10. Complete extended taxonomy of smart solutions.

multiple dimensions. These dimensions include material considerations, device longevity, and wider economic, social, and environmental impacts. While these technologies offer great promise, they also bring with them complexities that require careful consideration, particularly in terms of sustainability.

The material composition and lifespan of smart packaging play a crucial role in determining its overall sustainability. While there are general guidelines for sustainable packaging design (Sustainable Packaging Coalition, 2023), such as minimizing the number of materials used (Coelho et al., 2020;

Eriksen et al., 2019; Lofthouse et al., 2009 cited in Zhu et al., 2022), there remains a distinct lack of comprehensive and detailed design rules. This gap becomes even more pronounced apparent when considering the inherent complexity of integrating technologies into packaging (Barbero & Pereno, 2020). For example, while multi-material packaging is advantageous due to its enhanced functional benefits such as moisture and oxygen barriers, it poses significant economic and technical challenges when it comes to recycling (Sokka et al., 2024). Even when downcycling is possible, it often leads to substantial losses in both material quality and economic value, thereby limiting the potential for a truly sustainable material cycle (Sokka et al., 2024).

Economic viability is another critical factor, especially for small and medium-sized enterprises (SMEs). The significant financial burden associated with developing and implementing intelligent packaging can be a major hurdle. Packaging costs can potentially account for 50% to 100% of the total product cost (Müller & Schmid, 2019). This is a particular challenge in the food industry, where packaging costs are expected to remain below 10% of the total product value (Dainelli et al., 2008). These economic challenges raise concerns about the widespread adoption of intelligent packaging, as smaller companies may struggle to invest in such technologies. This could lead to a widening gap between large corporations and SMEs.

In addition, intelligent packaging presents several social implications, including potential changes in consumer behavior and the widening of the digital divide. While data carriers like QR codes are widely used due to their low cost and ease of use, more sophisticated sensors and indicators are not yet as widespread due to their higher costs (Müller & Schmid, 2019). Such technologies may also negatively impact consumer perceptions, potentially leading to increased food waste if consumers avoid products displaying discolored freshness indicators, even if the product remains safe for consumption (Müller & Schmid, 2019). Moreover, concerns regarding privacy and data generation by intelligent packaging may deter consumers who are increasingly wary of digital surveillance implications.

Another significant concern is the environmental impact. Although smart packaging can potentially reduce food waste

by optimizing inventory management and extending product shelf life, it also presents challenges related to material use and waste generation. The production of smart packaging often necessitates additional materials, potentially compromising sustainability goals by increasing resource consumption and waste generation (Müller & Schmid, 2019). Furthermore, the recyclability of these materials, particularly in multi-material packaging, poses a significant challenge, as it is often not economically viable to recycle (Sokka et al., 2024). The most significant applications of smart packaging technologies are evident in the pharmaceutical and food industries, as demonstrated by the collected case studies. These sectors have adopted smart packaging primarily for its clear advantages, including enhanced product safety, reduced waste, and improved supply chain traceability. However, despite these benefits, challenges persist regarding cost, material complexity, and consumer perception (Müller & Schmid, 2019; Dainelli et al., 2008). Nevertheless, this concentrated application within specific industries also highlights a significant opportunity for broader adoption of digital packaging technologies across other sectors. Integrating smart packaging could prove highly beneficial for sectors such as cosmetics or clothing, ensuring product integrity, enhancing the user experience, and providing real-time data on product conditions. The expansion of smart packaging into these novel domains has the potential to stimulate innovation and generate new business models, especially for companies looking to differentiate their products and contribute to a more sustainable and efficient global supply chain.

References

Barbero & Pereno, 2020
Barbero, S., & Pereno, A. (2020). *Packaging design in the digital age: A systemic approach to e-commerce*. Franco Angeli.

Brockgreitens & Abbas, 2016
Brockgreitens, J., & Abbas, A. (2016). Responsive food packaging: Recent progress and technological prospects. *Comprehensive Reviews in Food Science and Food Safety 15*(1): 3–15. https://doi.org/10.1111/1541-4337.12174

Ciravegna, 2010
Ciravegna, E. (2010). *La qualità del packaging*. Franco Angeli.

Ciravegna, 2017
Ciravegna, E. (2017). Diseño de packaging. Una aproximación sistémica a un artefacto complejo. *RChD: Creación y Pensamiento*, *2*(3), 1–17. https://doi.org/10.5354/0719-837X.2017.47825

Ciravegna, Pletto & Pasini, 2024
Ciravegna, E., Pletto, D., & Pasini, V. (2024). Desarrollo de métodos y herramientas para la industria del envasado: El papel mediador y facilitador del diseño. *Cuadernos del Centro de Estudios de Diseño y Comunicación*, *233*. https://doi.org/10.18682/cdc.vi233.11424

Coelho et al., 2020
Coelho, P. M., Corona, B., Ten Klooster, R., & Worrell, E. (2020). Sustainability of reusable packaging–Current situation and trends. *Resources, Conservation & Recycling: X*, *6*, 100037. https://doi.org/10.1016/j.rcrx.2020.100037

Dainelli et al., 2008
Dainelli, D., Gontard, N., Spyropoulos, D., Zondervan-van den Beuken, E., & Tobback, P. (2008). Active and intelligent food packaging: legal aspects and safety concerns. *Trends in Food Science & Technology*, *19*, S103–S112. https://doi.org/10.1016/j.tifs.2008.09.011

Ellen MacArthur Foundation, n.d.
Ellen MacArthur Foundation. (n.d.). *Circular economy introduction*. Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Eriksen et al., 2019
Eriksen, M. K., Damgaard, A., Boldrin, A., & Astrup, T. F. (2019). Quality assessment and circularity potential of recovery systems for household plastic waste. *Journal of Industrial Ecology*, *23*(1), 156–168. https://doi.org/10.1111/jiec.12822

European Commission, 2020
European Commission. (2020). *A new circular economy action plan for a cleaner and more competitive Europe*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

European Commission, 2022
European Commission. (2022). *Proposal for a regulation of the European Parliament and of the Council on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0677

Giardina, 2024
Giardina, C. (2024). *Advanced design for the extended packaging system. Piattaforma di servizi R&I per supportare una innovazione circolare e sostenibile negli imballaggi*. [Doctoral dissertation, Alma Mater Studiorum - Università di Bologna].

Kirchherr, Reike & Hekkert, 2017
Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kruijf et al., 2002
Kruijf, N. D., Beest, M. V., Rijk, R., Sipiläinen-Malm, T., Losada, P. P., & Meulenaer, B. D. (2002). Active and intelligent packaging: applications and regulatory aspects. *Food Additives & Contaminants*, *19*(S1), 144–162. https://doi.org/10.1080/02652030110072722

LaBerge et al., 2020
LaBerge, L., O'Toole, C., Schneider, J., & Smaje, K. (2020, October 5). *How COVID-19 has pushed companies over the technology tipping point–And transformed business forever*. McKinsey & Company. https://www.mckinsey.com/capabilities/strategy-and-corporate-finance/our-insights/how-covid-19-has-pushed-companies-over-the-technology-tipping-point-and-transformed-business-forever

Lao, Etrati & Narsalay, 2022
Lao, M., Etrati, A., & Narsalay, R. (2022, March 3). *Reinventing packaging*. Accenture. https://www.accenture.com/in-en/insights/industry-x/reinventing-packaging

Lichtenthaler, 2021
Lichtenthaler, U. (2021). Digitainability: The combined effects of the megatrends digitalization and sustainability. *Journal of Innovation Management*, *9*(2), 64–80. https://doi.org/10.24840/2183-0606_009.002_0006

Lofthouse, Trimingham & Bhamra, 2017
Lofthouse, V., Trimingham, R., & Bhamra, T. (2017). Reinventing refills: Guidelines for design. *Packaging Technology and Science*, *30*(12), 809–818. https://doi.org/10.1002/pts.2337

Lydekaityte & Tambo, 2020
Lydekaityte, J., & Tambo, T. (2020). Smart packaging: Definitions, models and packaging as an intermediator between digital and physical product management. *The International Review of Retail, Distribution and Consumer Research*, *30*(4), 377–410. https://doi.org/10.1080/09593969.2020.1724555

Marrone & Raimo, 2021
Marrone, A., & Raimo, N. (2021). *Sostenibilità e digitalizzazione, un approccio economico-aziendale*. Giuffrè.

Moghrabi et al., 2023
Moghrabi, I. A. R., Bhat, S. A., Szczuko, P., AlKhaled, R. A., & Dar, M. A. (2023). Digital transformation and its influence on sustainable manufacturing and business practices. *Sustainability*, *15*(4), 3010. https://doi.org/10.3390/su15043010

Müller & Schmid, 2019
Müller, P., & Schmid, M. (2019). Intelligent packaging in the food sector: A brief overview. *Foods*, *8*(1), 16. https://doi.org/10.3390/foods8010016

Nandanwade Priyanka & Nathe Parag, 2013
Nandanwade Priyanka, C., & Nathe Parag, D. (2013). Intelligent and active packaging. *International Journal of Engineering and Management Sciences*, *4*(4), 417–418. http://scienceandnature.org/IJEMS-Vol4(4)-Oct2013/IJEMS_V4(4)2013-2.pdf

Nilsson et al., 2012
Nilsson, H.-E., Unander, T., Siden, J., Andersson, H., Manuilskiy, A., Hummelgard, M., & Gulliksson, M. (2012). System integration of electronic functions in smart packaging applications. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, *2*(10), 1723–1734. https://doi.org/10.1109/TCPMT.2012.2204056

Ozcan, 2020
Ozcan, A. (2020). New approaches in smart packaging technologies. In *Proceedings of the 10th International Symposium on Graphic Engineering and Design, GRID* (pp. 21–37). https://doi.org/10.24867/GRID-2020-p1

Palazzo, Vollero & Siano, 2023
Palazzo, M., Vollero, A., & Siano, A. (2023). Intelligent packaging in the transition from linear to circular economy: driving research in practice. *Journal of Cleaner Production*, *388*, 135984. https://doi.org/10.1016/j.jclepro.2023.135984

Purvis, Mao & Robinson, 2019
Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, *14*(3), 681–695. https://doi.org/10.1007/s11625-018-0627-5

Schaefer & Cheung, 2018
Schaefer, D., & Cheung, W. M. (2018). Smart packaging: opportunities and challenges. *Procedia Cirp*, *72*, 1022–1027. https://doi.org/10.1016/j.procir.2018.03.240

Sokka et al., 2024
Sokka, L., Välimäki, M., Väisänen, K. L., Keskinen, J., Hakola, E., Mäntysalo, M., Ollila, J., Happonen, T., Hakola, L., & Smolander, M. (2024). Life cycle assessment of a new smart label for intelligent packaging. *Flexible and Printed Electronics*, *9*(1), 015007. https://doi.org/10.1088/2058-8585/ad2279

Sustainable Packaging Coalition, 2023
Sustainable Packaging Coalition. (2023). *Definition of sustainable packaging*. https://sustainablepackaging.org/wp-content/uploads/2024/01/SPC_Definition-of-Sust-Packaging_Landscape.pdf

Zhu, 2022
Zhu, Z., Liu, W., Ye, S., & Batist,a L. (2022). Packaging design for the circular economy: A systematic review. *Sustainable Production and Consumption*, *32*, 817–832. https://doi.org/10.1016/j.spc.2022.06.005

FUTURE-PACK. LIFE CYCLE SUSTAINABILITY ASSESSMENT IN ADVANCED PACKAGING DESIGN

Erik Ciravegna, Caterina Antonia Dattilo**, Massimo Delogu**, Veronica Pasini**

1. Introduction

The term "Digitainability" has recently been proposed (Gupta et al., 2020; Lichtenthaler, 2021) to refer the combination of the two megatrends of *sustainability* and *digitalization* and their potential cross-fertilization effects on markets and different production sectors. On the one hand, the consolidation of the circular economy (Ellen MacArthur Foundation, n.d.; European Commission, 2020), together with the increasing regulation of packaging waste—such as the so-called PPWR (European Commission, 2022)—and growing consumer concern about sustainability (Bar Am et al., 2023), is forcing companies to rethink products and processes to reduce their impact and improve their utility (Marrone & Raimo, 2021). On the other hand, technological innovation, with the ongoing proliferation of digital devices and social media fueled by COVID-19 (LaBerge et al., 2020), creates significant challenges, but also transformational opportunities for sustainable production and business practices (Moghrabi et al., 2023).

In this framework and as part of the research activities of the MICS extended partnership, the study *FuturE-Pack. Digital Advanced Design for the Enhancement of Packaging as a 'Broadcaster' in the Made in Italy Supply Chain* (Project 1.1)—involving researchers from three universities (University of Bologna, University of Florence and Polytechnic University of Turin)—explores the application of digital solutions to enhance packaging as a communication device (Ciravegna, 2010; 2017; Buchetti & Ciravegna, 2009; Bucchetti, 2005) for the exchange of relevant information within the Made in Italy sectors: digital technology is transforming packages into intelligent devices able to track and monitor the integrity and safety of goods, potentially recording the entire history of products and the impacts gener-

**Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

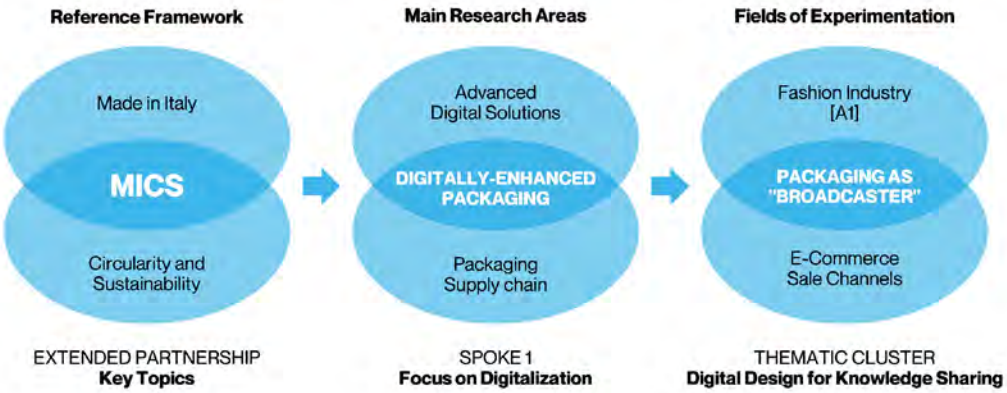
***Department of Industrial Engineering, University of Florence, Italy*

ated along their supply chains, while conveying the identity and values of brands.

The above aspects become even more relevant in light of the entry into force of the EU's Ecodesign for Sustainable Products Regulation (ESPR) and, as one of its fundamental tools, the introduction of the Digital Product Passport (DPP) (European Commission, n.d.), which will provide information on the environmental sustainability of products, with the aim of improving traceability and transparency along the entire value chain and improving the management and exchange of product data, which are crucial for ensuring their sustainable use, extending their life, and circularity. Digitally enhanced solutions applied to packaging and product labelling, in this sense, can play a significant role in archiving and communicating relevant data referred to DPP, extending the information collected also to the social and economic sustainability of the products in addition to the environmental one, thanks to the application of appropriate assessment methods such as Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC), and the adoption of a systemic approach leading to a comprehensive Life Cycle Sustainability Assessment (LCSA).

The research work to date has been geared toward mapping and analyzing the state of the art by collecting relevant case studies of existing digital solutions—already being applied or potentially applicable to packaging—and the functionalities they enable. In addition, a review of the scientific literature (see appendix) inherent to the LCA of products and their impacts has been carried out, according to the three pillars of sustainability (Purvis et al., 2019): *planet* (environmental), *people* (social) and *profit* (economical). Future research will focus on the analysis of the supply chain and the ecosystem of stakeholders related to packaged goods, in particular the e-commerce channel and the fashion industry (A1 sector), which are the areas of analysis and experimental work of the project.

This essay intends to focus on the second line of work carried out so far and presents the research developed to deepen LCSA as an integrated methodology to assess products triple impacts, and the definition of a systematized conceptual grid concerning sustainability issues. Furthermore, methods and tools for the life cycle assessment of products and for the evaluation of



1. Conceptual framework and structuring of the project.
All images are reproduced in color in the online edition of the book.

their impacts are currently being studied, together with examples from other sectors and for other purposes, with the goal of developing, as one of the expected outcomes of the project, a set of solutions (guidelines, recommendations, checklists, best practices, etc.) to be provided to stakeholders in the Made in Italy supply chain, to improve traceability and transparency in product information.

1. Assessing the triple impacts of products

1.1. Life Cycle Sustainability Assessment

The recent growth of e-commerce has led to a significant increase in the use of packaging, causing environmental issues (Oláh et al., 2023; Haryanti & Subriadi, 2022). The current state of packaging in e-commerce highlights some important gaps, such as: overpackaging which should be a concern for policymakers; commonly used plastic packaging; package distribution has a large impact on the environment (Escursell et al., 2021). For these reasons, new approaches to reduce the environmental impact of packaging, should be pursued, such as: biodegradation of cardboard waste from online shopping; implementation of clear guidelines and policies to prevent overpackaging; encouraging circular packaging through clear design guidelines; exploring 3D printing for minimal-material packaging solutions; evaluating new logistics strategies in terms of their environmental friendliness; conducting advance LCA studies to ensure a lower carbon footprint compared to existing packaging.

With regard to the last point, concerning LCA, it is important to emphasize that sustainability includes not only environmental protection but also social/ethical, and economic aspects. This means that a comprehensive life cycle (LC) approach is required to evaluate design alternatives. LCSA is considered the most appropriate methodology for assessing the sustainability of products and processes, integrating LCA (International Organization for Standardization, 2006a; 2006b), LCC (Hunkeler et al., 2008; Swarr et al., 2011) and S-LCA (Benoît & Mazijn, 2009).

There are two main approaches to life cycle-based sustainability assessment. The first, proposed by Kloepffer (2008)

and Finkbeiner et al. (2010), extends ISO-LCA to include economic and social aspects, following the *triple bottom line* model. The second, proposed by Guinée et al. (2011), is an integrated framework that combines the conventional LCA with economic and social aspects, allowing for in-depth analysis at different levels. Both approaches aim to broaden sustainability assessment from the environment to economic and social spheres but differ in conceptual structure and modeling principles. The LCSA analysis approach integrates inventory and impact assessment into a single modeling phase, while the LCSA assessment approach is more suitable for product-level applications.

However, the three methodologies (LCA, LCC, and S-LCA) inherently demonstrate different features and levels of maturity, requiring specific considerations for a complete sustainability assessment. Challenges and opportunities for improvement concern each phase of LCSA, such as goal and scope definition, indicator selection, and integration and presentation of results. For example, selecting indicators for the social dimension is complex due to the lack of a clear selection process (Zanchi et al., 2021).

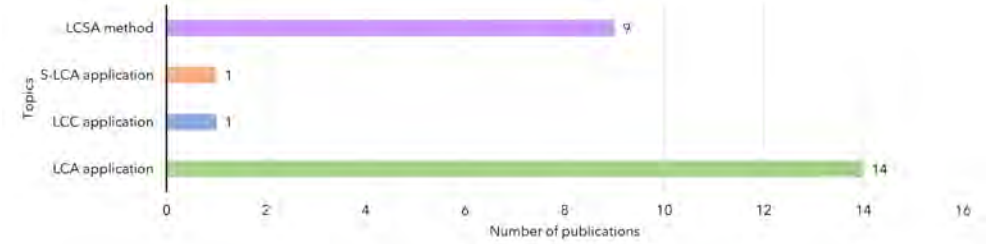
1.2. Products impacts: literature review

As explained in the previous paragraph, the LCSA plays a pivotal role in evaluating and validating the threefold impact of products on the environment, society, and the economy. In the context of this project, the methodology focuses on packaged goods, particularly those in the e-commerce, and the fashion industry, placing special emphasis on products that bear the Made in Italy label or are locally sourced. In this section, the literature review is presented considering a scientific methodology (implemented in an Excel spreadsheet) which includes three main steps (fig. 2): 1) meta-analytic approach; 2) review; 3) analysis.

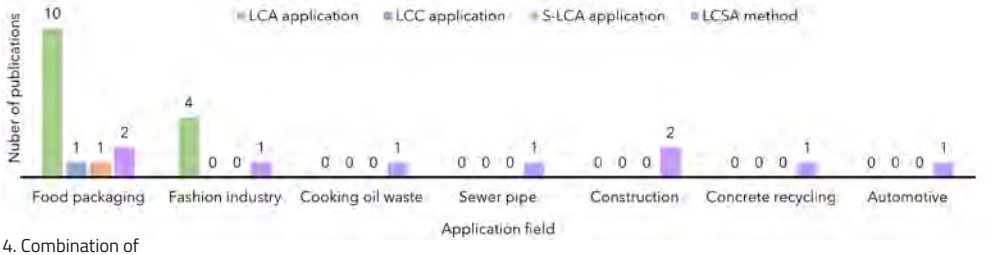
The meta-analytic approach consists of: *Research Sources*, that are multiple platforms from which it is possible to find all the documents that provide information and consequently knowledge (e.g., Google Scholar, IEEE Explore, Scopus database, Science Direct); *Specific Topics*, that are all the considered topics (i.e., LCA application, LCC application, S-LCA application, LCSA method).



2. Scientific approach to literature analysis.



3. Topics trend.



4. Combination of application fields and topics trend.

The second step of the methodology is about the critical review of the literature relating to the project; it is organized into different sections: *General Characteristics* including the title, author(s), year of publication, geographical location or where the work was carried out (e.g., Organization, University), type of publication, and journal; *Specific Characteristics* that are abstract and keywords (i.e., the words or phrases that are suggested by the authors of the documents to facilitate their search); *Application*, by which the documents are grouped according to the application fields.

Finally, the literature "analysis" is carried out considering the categories listed below: *Topics Trend*, which are the topics chosen for the literature analysis according to the search categories; *Time Trend* is the time trend of the considered publications; *Geographical References* are the geographical references associated with the generic article analyzed in the specific review phase; *Type of Publications*, such as paper, review, report, thesis, conference paper.

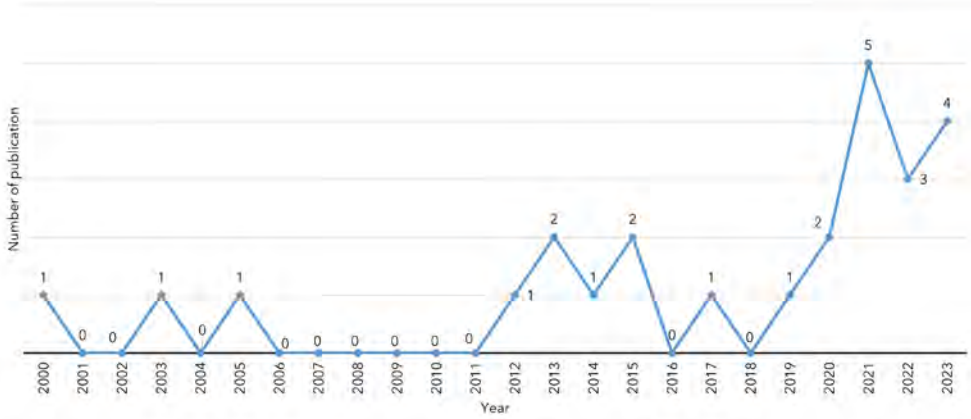
Based on an analysis of 25 publications (see Annex), we have graphed the trend of various topics (fig. 3). Notably, "LCA application" was the most discussed topic (14 mentions), followed by "LCSA method" (9 mentions). Conversely, "S-LCA application" and "LCC application" each had only one mention.

The bar graph in figure 4 reveals the compelling results of combining search categories and topic trends. It's evident that *Food Packaging* is a dominant topic across multiple categories, including *LCA Application* and *LCSA Method*. Similarly, the *Fashion Industry* category showcases significant publications related to both *LCA Application* and *LCSA Method*. While other categories have fewer publications, they still contribute to the diverse landscape of research.

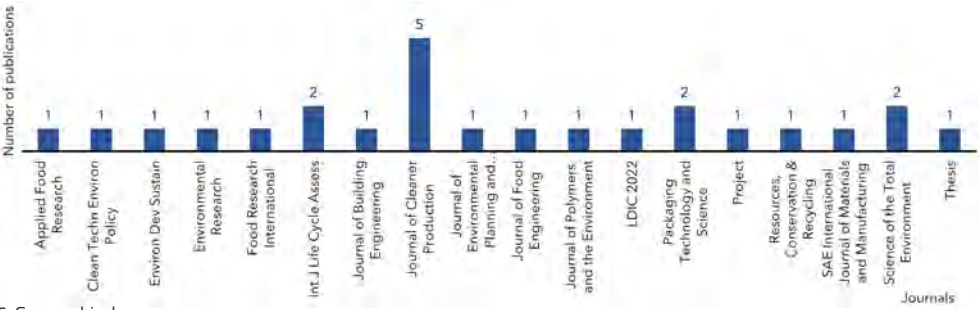
The data from 2000 to 2023, as shown in figure 5, reveals a rising trend in publications with a peak in 2021. However, there has been a slight decrease in the last three years (2021-2023).

The analysis of the geographical reference (fig. 6) indicates that numerous countries have undertaken sustainability analyses across various fields. Notably, Italy (6) and Canada (3) have emerged as the leading publishers in this regard.

Figure 7 illustrates the publications categorized by geographical area and search criteria. This analysis demonstrates



5. Time trend.



6. Geographical references.



7. Combination of geographical references and application fields.

that Italian research is concentrated on *Food Packaging* and *Automotive*, while Canada has produced research across all three categories. Furthermore, the *Fashion Industry* research is being conducted in various countries including Australia, Austria, Canada, Stockholm, and the UK.

The scientific journal is the most frequently used type of publication, accounting for 72% of the total analyzed works (fig. 8).

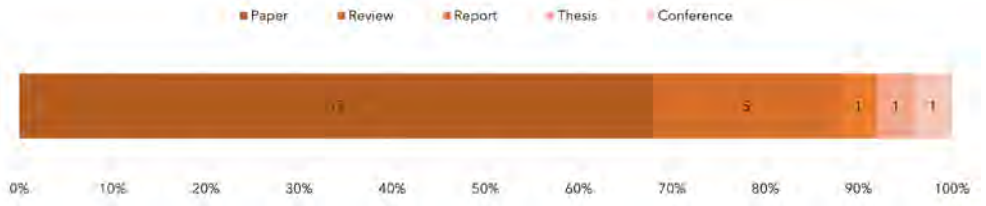
The analysis involved combining the types of journals with the trending topics (fig. 9) and the application fields (fig. 10). The bar chart in figure 9 reveals that numerous journals are focused on addressing sustainability issues, indicating a growing interest in this area.

When reviewing both diagrams simultaneously, it becomes evident that the topic of LCA is widely discussed in scientific journals, particularly in the fields of *Food Packaging* and the *Fashion Industry*. Furthermore, the LCSA method is a compelling and versatile topic that has significant implications across various fields of application (fig. 10).

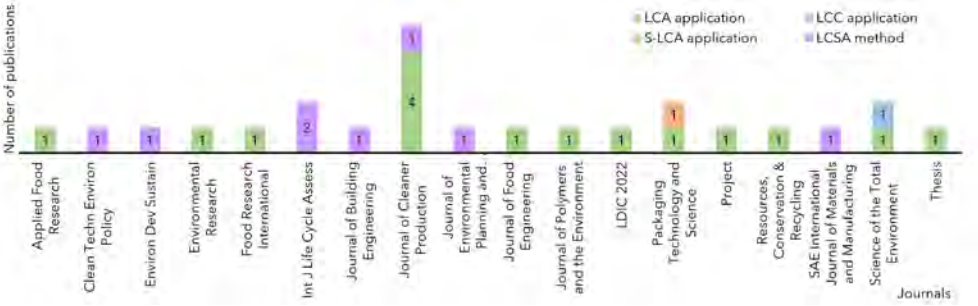
1.3. A conceptual grid on sustainability issues: a basis for a systemic approach

Based on the review of scientific literature—including ISO and UNI EN ISO standards—a scenario regarding the potential for use and opportunities of LCSA has been outlined; also, the indicators for assessing product impacts were detailed and systematized, to define an overall conceptual grid that takes into account environmental (European Commission et al., 2010a; 2010b; 2011; International Standards Organization, 2006a; 2006b; UNI Ente Italiano di Normazione, 2021a; 2021b), economic (International Organization for Standardization, 2017; 2019; Swarr et al., 2011) and social (Benoît & Mazijn, 2009; Blanco & Finkbeiner, 2015; Goedkoop et al., 2020; Benoît et al., 2020; International Standards Organization, n.d.) factors.

The indicators considered in the LCA application are as follows: *climate change*; *ozone depletion*; *human toxicity*; *respiratory inorganics/particulate matter*; *ionizing radiation*; *photochemical ozone formation*; *acidification*; *eutrophication*; *ecotoxicity*; *land use*; *resource depletion*. Those considered in the LCC application are:



8. Type of publication.



9. Combination of journals and topics trend.



10. Combination of journals and application fields.

raw material cost; *production cost*; *use cost*; *end-of-life cost*. Finally, the application of S-LCA considers aspects referring mainly to workers: *Health and Safety*, which includes the number of hours of health and safety training per worker given during the reporting period, and the average rate of incidents during the reporting period; *Wages*, regarding the percentage of workers whose wages meet at least legal, or industry minimum standards and their provision fully complies with all applicable laws, and the percentage of workers who are paid a living wage; *Discrimination*, which indicates the number of complaints identified during the reporting period related to discrimination; *Training and Education*, referred to the numbers of hours of training per employee during the reporting period; *Child Labour*, that is, the number of hours of child labour identified during the reporting period.

The conceptual grid described above, to be further explored and possibly integrated with other indicators (e.g., social factors could also include aspects referring to people in general and society, not just workers), can become the basis for an overall systemic approach to assessing the impacts of products, from an LCSA perspective.

2. Methods and tools for sustainability assessment

2.1. Research and collection of assessment methods and tools

As already mentioned, the "FuturE-Pack" project's objectives include delving into LCSA as an integrated methodology for assessing the triple impacts of products; based on this in-depth research, a systematized conceptual grid related to sustainability issues was defined.

In addition, case studies of methods and tools already applied in product lifecycle assessment are currently being collected, both for technical-scientific and educational purposes, as well as examples from other sectors and for other uses. This work aims at gathering design references and inspirations for developing solutions (guidelines, recommendations, checklists, best practices, etc.) through which the systematized conceptual grid already described could be applied. The goal is to provide the stakeholders in the Made in Italy supply chain with a set of tools to improve traceability and transparency of product

information, to be communicated through digitally enhanced packaging.

A total of 25 case studies have been collected so far, including self-assessment tools, toolkits, manuals, guidelines and checklists, in the form of software, interactive platforms and downloadable static documents.

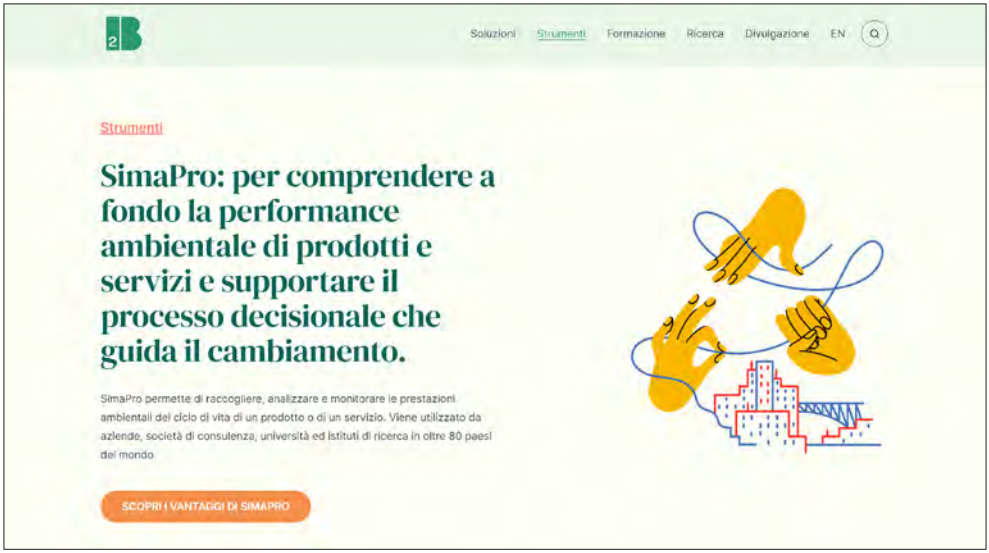
Both quantitative and qualitative approaches were considered. The primary areas of interest covered are: sustainability and circularity, design, and packaging. Examples of the case studies collected are shown in figures 11 and 12. This work is currently under development.

2.2. Cataloguing and analysis of assessment methods and tools

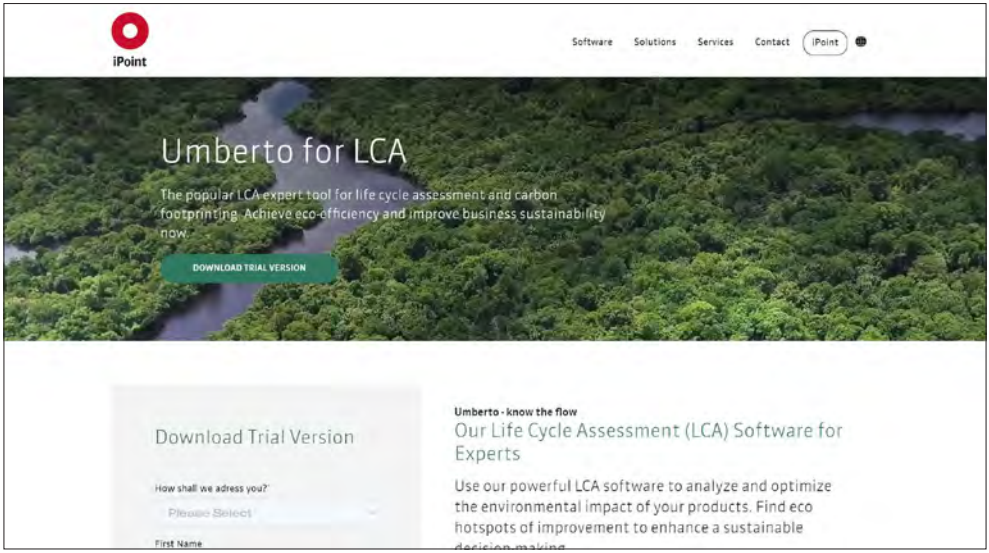
To catalog each case study and gather relevant information for the project, a worksheet was constructed with the following preliminary descriptive and analysis categories: title and general description; sources of information and other available references (web/video links); indication of whether the case study is related to packaging, e-commerce, fashion, design, and sustainability; type of support (software, interactive platforms and downloadable static documents); type of interface (static, dynamic, interactive); language (more informal and divulgatory, or more formal and technical-scientific); approach (quantitative, qualitative); content (text, game, map/graphic, open-ended or multiple-choice questions).

To facilitate cataloging work, based on the categories mentioned, a systematized database was developed through an online service (fig. 13), which allowed for more agile management of the information and documentation associated with the various case studies collected. This database will be supplemented with new cases and will constitute an open repository for future implementations.

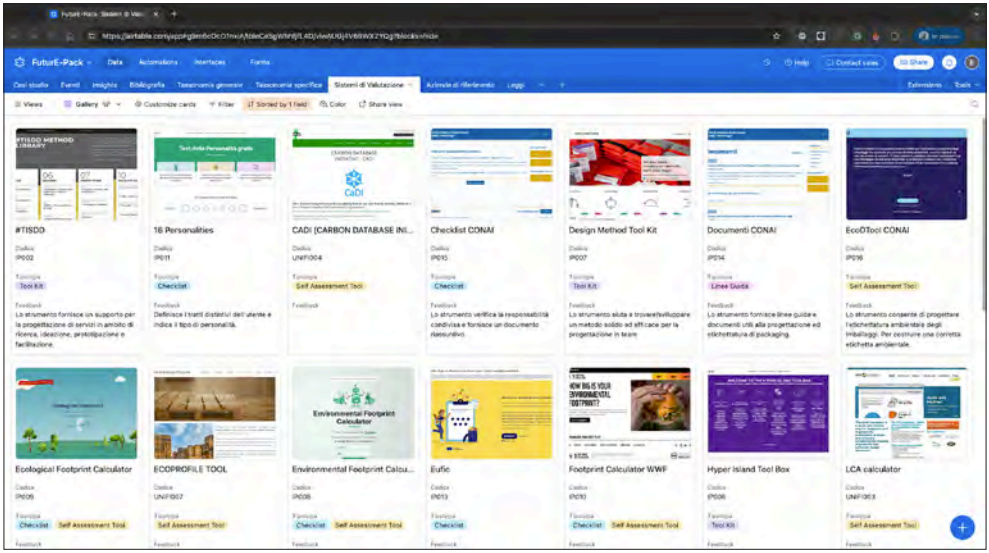
In a similar way to the literature review, from the information collected in the worksheets and by cross-referencing the data obtained, appropriate visual synthesis maps will be produced, one for each variable or groups of variables considered, which will guide the reading of the mapping results and obtain a clearer picture of the state of the art and useful insights for the subsequent development of the project.



11. Example of a tool for assessing the environmental performance of products: SimaPro.



12. Example of Life Cycle Assessment (LCA) software: Umberto for LCA.



13. Systematized online database of collected methods and tools.

3. Conclusions

The research presented herein has explored the use of LCSA as an integrated methodology for evaluating the triple bottom line impacts of products and has established a systematized conceptual framework to address sustainability concerns. The literature review and subsequent systematization process have led to the creation of a conceptual grid on sustainability issues, useful for analyzing the state of the art, as well as the systematic collection of relevant methods and tools for impacts assessment. The next steps of this research phase involve the revision and integration of this conceptual grid, with particular attention to highlighting social aspects, which are currently limited to indicators related to workers directly involved. Expanding social impact analysis beyond workers to include local communities and end-users, as well as considering the role of packaging in society (e.g., through messages conveyed), leads to a more comprehensive understanding of long-term effects. This broader approach ensures balanced assessments by incorporating diverse perspectives, facilitates the development of effective mitigation strategies, and fosters social responsibility, leading to more informed and sustainable consumer decisions.

Furthermore, it is crucial to continue expanding the collection and analysis of assessment methods and tools, exploring novel applications beyond the current scope. This will broaden the analytical perspective, thereby enhancing the overall quality of evaluations and fostering the development and dissemination of valuable tools and methods for future designers. Utilizing specific Key Performance Indicators (KPIs) is imperative for developing scientifically rigorous methods and tools. KPIs provide a framework for assessing product or service impacts, facilitating data-driven decision-making, promoting transparency, and enabling continuous improvement. These quantifiable metrics (Giorgi et al., 2017) allow for objective impact evaluation and comparability over time. Additionally, KPIs serve as crucial communication tools, enhancing understanding and demonstrating transparency and social responsibility to stakeholders.

While acknowledging the inherent uncertainty in even the most effective measurement techniques (Kerzner, 2023), and recognizing that perfect information for decision-making is un-

attainable, the selection of appropriate KPIs remains vital for approximating desired analytical outcomes. Therefore, a crucial next step in this project is the precise definition of KPIs. This will ensure transparency from the outset and establish a robust methodological foundation for future analyses and evaluations. KPIs can provide data that empowers designers and planners to critically reflect on their projects, identify areas for improvement, and foster a feedback loop essential for the evolution of design expertise and driving innovation within the process itself.

References

Bar Am et al., 2023
Bar Am, J., Doshi, V., Malik, A., Noble, S., & Frey, S. (2023, February 6). *Consumers care about sustainability–and back it up with their wallets.* https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/consumers-care-about-sustainability-and-back-it-up-with-their-wallets#/

Benoît, & Mazijn, 2009
Benoît, C., & Mazijn, B. (Eds.) (2009). *Guidelines for social life cycle assessment of products*. United Nations Environment Programme.

Benoît et al., 2020
Benoît, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck Mankaa, R., Russo Garrido, S., Berger Tragnone, B. M, Valdivia, S., Lehmann, A., Finkbeiner, M., & Arcese, G. (Eds.) (2020). *Guidelines for social life cycle assessment of products and organizations 2020*. United Nations Environment Programme.

Blanco & Finkbeiner, 2015
Blanco, J. M., & Finkbeiner, M. (Eds.) (2015). *Guidance on organizational life cycle assessment*. United Nations Environment Programme.

Bucchetti, 2005
Bucchetti, V. (2005). *Packaging design: storia, linguaggi, progetto*. Franco Angeli.

Bucchetti & Ciravegna, 2009
Bucchetti, V. & Ciravegna, E. (2009). *Le parole del packaging: Glossario ragionato per il sistema-imballaggio*. Edizioni Dativo.

Ciravegna, 2010
Ciravegna, E. (2010). *La qualità del packaging*. Franco Angeli.

Ciravegna, 2017
Ciravegna, E. (2017). Diseño de packaging. Una aproximación sistémica a un artefacto complejo. *RChD: Creación y Pensamiento*, *2*(3), 1–17. https://doi.org/10.5354/0719-837X.2017.47825

Ellen MacArthur Foundation, n.d.
Ellen MacArthur Foundation. (n.d.). *Circular economy introduction*. https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Escursell, Llorach-Massana & Roncero, 2021
Escursell, S., Llorach-Massana, P., & Roncero, M. B. (2021). Sustainability in e-commerce packaging: a review. *Journal of Cleaner Production*, *280*, 124314. https://doi.org/10.1016/j.jclepro.2020.124314

European Commission, 2020
European Commission. (2020). *A new circular economy action plan for a cleaner and more competitive Europe*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

European Commission, 2022
European Commission. (2022). *Proposal for a regulation of the European Parliament and of the Council on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0677

European Commission, n.d.
European Commission. (n.d.). *Ecodesign for sustainable products regulation*. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en

European Commission et al., 2010a
European Commission, Joint Research Centre, & Institute for Environment and Sustainability. (2010a). *International Reference Life Cycle Data System (ILCD) Handbook–general guide for life cycle assessment–Detailed guidance*. Publications Office of the European Union. https://eplca.jrc.ec.europa.eu/ilcd.html

European Commission et al., 2010b
European Commission, Joint Research Centre, & Institute for Environment and Sustainability. (2010b). *International Reference Life Cycle Data System (ILCD) Handbook–framework and requirements for life cycle impact assessment models and indicators*. Publications Office of the European Union. https://eplca.jrc.ec.europa.eu/ilcd.html

European Commission et al., 2011
European Commission, Joint Research Centre, & Institute for Environment and Sustainability. (2011). *International Reference Life Cycle Data System (ILCD) Handbook–recommendations for life cycle impact assessment in the European context*. Publications Office of the European Union. https://eplca.jrc.ec.europa.eu/ilcd.html

Finkbeiner et al., 2010
Finkbeiner, M., Schau, E. M., Lehmann, A., & Traverso, M. (2010). Towards life cycle sustainability assessment. *Sustainability*, *2*(10), 3309–3322. https://doi.org/10.3390/su2103309

Giorgi, Lavagna & Campioli, 2017
Giorgi, S., Lavagna, M., & Campioli, A. (2017). Economia circolare, gestione dei rifiuti e Life Cycle Thinking: fondamenti, interpretazioni e analisi dello stato dell'arte. *Ingegneria dell'Ambiente*, *4*(3). https://doi.org/10.14672/ida.v4i3.1141

Goedkoop et al., 2020
Goedkoop, M. J., de Beer, I. M., Harmens, R., Saling, P., Morris, D., Florea, A., Hettinger, A. L., Indrane, D., Visser, D., Morao, A., Musoke-Flores, E., Alvarado,

C., Rawat, I., Schenker, U., Head, M., Collotta, M., Andro, T., Viot, J. F., & Whatelet, A. (2020). *Product social impact assessment handbook 2020*. https://www.social-value-initiative.org/download/

Guinée & Heijungs, 2011
Guinée, J. B., & Heijungs, R. (2011). Life cycle sustainability analysis: framing questions for approaches. *Journal of Industrial Ecology*, *15*(5), 656–658. https://doi.org/10.1111/j.1530-9290.2011.00398.x

Gupta, Motlagh & Rhyner, 2020
Gupta, S., Motlagh, M., & Rhyner, J. (2020). The digitalization sustainability matrix: A participatory research tool for investigating digitainability. *Sustainability*, *12*(21), 9283. https://doi.org/10.3390/su12219283

Haryanti & Subriadi, 2022
Haryanti, T., & Subriadi, A. P. (2022). E-commerce acceptance in the dimension of sustainability. *Journal of Modelling in Management*, *17*(2), 715–745. https://doi.org/10.1108/JM2-05-2020-0141

Hunkeler, Lichtenvort & Rebitzer, 2008
Hunkeler, D., Lichtenvort, K., & Rebitzer, G. (2008). *Environmental life cycle costing*. CRC Press. https://doi.org/10.1201/9781420054736

International Organization for Standardization, 2006a
International Organization for Standardization. (2006a). *Environmental management – Life cycle assessment – Principles and framework (ISO 14040:2006)*.

International Organization for Standardization, 2006b
International Organization for Standardization. (2006b). *Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006)*.

International Organization for Standardization, 2017
International Organization for Standardization. (2017). *Buildings and constructed assets – Service-life planning – Part 5: Life-cycle costing (ISO 15686-5:2017)*.

International Organization for Standardization, 2019
International Organization for Standardization. (2019). *Monetary valuation of environmental impacts and related environmental aspects (ISO 14008:2019)*.

International Organization for Standardization, n.d.
International Organization for Standardization. (n.d.). *Environmental management – Principles and framework for social life cycle assessment* (ISO/FDIS 14075, Final Draft International Standard in Approval Phase).

Kerzner, 2022
Kerzner, H. (2022). *Project management metrics, KPIs, and dashboards: a guide to measuring and monitoring project performance* (4th ed.). John Wiley & Sons. AIPIA, Active & Intelligent Packaging Industry Association. http://www.aipia.info

Kloepffer, 2008
Kloepffer, W. (2008). Life cycle sustainability assessment of product. *The International Journal of Life Cycle Assessment*, *13*(2), 89–95. https://doi.org/10.1065/lca2008.02.376

LaBerge et al., 2020
LaBerge, L., O'Toole, C., Schneider, J., & Smaje, K. (2020, October 5). *How*

COVID-19 has pushed companies over the technology tipping point–and transformed business forever. McKinsey & Company. https://www.mckinsey.com/capabilities/strategy-and-corporate-finance/our-insights/how-covid-19-has-pushed-companies-over-the-technology-tipping-point-and-transformed-business-forever

Lao, Etrati & Narsalay, 2022
Lao, M., Etrati, A., & Narsalay, R. (2022, March 3). *Reinventing packaging*. Accenture. https://www.accenture.com/in-en/insights/industry-x/reinventing-packaging

Lichtenthaler, 2021
Lichtenthaler, U. (2021). Digitainability: The combined effects of the megatrends digitalization and sustainability. *Journal of Innovation Management*, *9*(2), 64–80. https://doi.org/10.24840/2183-0606_009.002_0006

Marrone & Raimo, 2021
Marrone, A., & Raimo, N. (2021). *Sostenibilità e digitalizzazione, un approccio economico-aziendale*. Giuffrè.

Moghrabi et al., 2023
Moghrabi, I. A. R., Bhat, S. A., Szczuko, P., AlKhaled, R. A., & Dar, M. A. (2023). Digital transformation and its influence on sustainable manufacturing and business practices. *Sustainability*, *15*(4), 3010. https://doi.org/10.3390/su15043010

Oláh et al., 2023
Oláh, J., Popp, J., Khan, M. A., & Kitukutha, N. (2023). Sustainable e-commerce and environmental impact on sustainability. *Economics and Sociology*, *16*(1), 85–105. https://doi.org/10.14254/2071-789X.2023/16-1/6

Purvis, Mao & Robinson, 2019
Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, *14*(3), 681–695. https://doi.org/10.1007/s11625-018-0627-5

Swarr et al., 2011
Swarr, T. E., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A. C., & Pagan, R. (2011). Environmental life-cycle costing: A code of practice. *The International Journal of Life Cycle Assessment*, *16*(5), 389–391. https://doi.org/10.1007/s11367-011-0287-5

UNI Ente Italiano di Normazione, 2021a
UNI Ente Italiano di Normazione. (2021a). *Gestione ambientale - Valutazione del ciclo di vita - Principi e quadro di riferimento (UNI EN ISO 14040:2021)*.

UNI Ente Italiano di Normazione, 2021b
UNI Ente Italiano di Normazione. (2021b). *Gestione ambientale - Valutazione del ciclo di vita - Requisiti e linee guida (UNI EN ISO 14044:2021)*.

Zanchi et al., 2021
Zanchi, L., Delogu, M., Dattilo, C. A., Zamagni A., & Del Pero, F. (2021). Integrating Life Cycle Sustainability Assessment Results Using Fuzzy-TOPSIS in Automotive Lightweighting. *SAE International Journal of Materials and Manufacturing*, *14*(3), 317–341. https://doi.org/10.4271/05-14-03-0022

Annex

Details of the 25 publications used for the literature review are presented in the table below.

N.	Publication	Keywords	Type of publication	Assessment Method	Scope of Application
1	Larsen, G. V., Tollin, N., Sattrup, P. A., Birkved, M., & Holmboe, T. (2022). What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. *Journal of Building Engineering, 50*, 104203. https://doi.org/10.1016/j.jobe.2022.104203	> Life Cycle Sustainability Assessment (LCSA) > Social Life Cycle Assessment (S-LCA) > Circular economy > Sustainable building > Built environment	Review	LSCA method	Construction
2	Hossaini, N., Reza, B., Akhtar, S., Sadiq, R., & Hewage, K. N. (2015). AHP based life cycle sustainability assessment (LCSA) framework: A case study of six storey wood frame and concrete frame buildings in Vancouver. *Journal of Environmental Planning and Management, 58*(7), 1217–1241. https://doi.org/10.1080/09640568.2014.920704	> Life Cycle Assessment (LCA) > Sustainability assessment > Concrete frame	Paper	LSCA method	Construction
3	Vinyes, E., Oliver-Solà, J., Ugaya, C., Rieradevall, J., & Gasol, C. M. (2013). Application of LCSA to used cooking oil waste management. *The International Journal of Life Cycle Assessment, 18*(2), 445–455. https://doi.org/10.1007/s11367-012-0482-z	> Life Cycle Assessment (LCA) > Life Cycle Costing (LCC) > Social assessment > Sustainability	Paper	LSCA method	Cooking Oil Waste
4	Akhtar, S., Reza, B., Hewage, K., Shahriar, A. Zargar, A., & Sadiq, R. (2015). Life cycle sustainability assessment (LCSA) for selection of sewer pipe materials. *Clean Technologies and Environmental Policy, 17*(4), 973–992. https://doi.org/10.1007/s10098-014-0849-x	> Sewer pipe materials > Life Cycle Sustainability Assessment (LCSA) > Energy synthesis > Multi-Criteria Decision-Making (MCDM) method	Original paper	LSCA method	Sewer Pipe

N.	Publication	Keywords	Type of publication	Assessment Method	Scope of Application
5	Hu, M., Kleijn, R., Bozhilova-Kisheva, K. P., & Di Maio, F. (2013). An approach to LCSA: the case of concrete recycling. *The International Journal of Life Cycle Assessment*, *18*(9), 1793–1803. http://dx.doi.org/10.1007/s11367-013-0599-8	> Construction and demolition waste > End-of-life concrete recycling > Life Cycle Sustainability Analysis (LCSA) > Life Cycle Sustainability Assessment (LCSA)	Paper	LSCA method	Concrete Recycling
6	Zanchi, L., Delogu, M., Dattilo, C. A., Zamagni A., & Del Pero, F. (2021). Integrating Life Cycle Sustainability Assessment Results Using Fuzzy-TOPSIS in Automotive Lightweighting. *SAE International Journal of Materials and Manufacturing*, *14*(3), 317–341. https://doi.org/10.4271/05-14-03-0022	> Life Cycle Sustainability Assessment (LCSA) > Fuzzy-TOPSIS > Light weighting > Automotive	Paper	LSCA method	Automotive
7	Foolmaun, R. K., & Ramjeawon, T. (2013). Life cycle sustainability assessments (LCSA) of four disposal scenarios for used polyethylene terephthalate (PET) bottles in Mauritius. *Environment, Development and Sustainability*, *15*(3), 783–806. https://doi.org/10.1007/s10668-012-9406-0	> Life Cycle Sustainability Assessment (LCSA) > Life Cycle Assessment (LCA) > Life cycle costing, social life cycle assessment > Analytical hierarchy process, PET bottles	Paper	LSCA method	Food Packaging
8	Ferrara, C. & De Feo, G. (2020). Comparative life cycle assessment of alternative systems for wine packaging in Italy. *Journal of Cleaner Production*, *259*, 1–12. https://doi.org/10.1016/j.jclepro.2020.120888	> Aseptic carton > Bag-in-box > Glass > PET > Recycling >Sustainability	Paper	LCA application	Food Packaging
9	Tamburini, E., Costa, S., Summa, D., Battistella, L., Fano, E. A., & Castaldelli, G. (2021). Plastic (PET) vs bioplastic (PLA) or refillable aluminium bottles–What is the most sustainable choice for drinking water? A life-cycle (LCA) analysis. *Environmental Research*, *196*, 110974. https://doi.org/10.1016/j.envres.2021.110974	> PET bottle > PLA bottle > Aluminium refillable bottle > LCA > Sustainability > Water quality	Paper	LCA application	Food Packaging

N.	Publication	Keywords	Type of publication	Assessment Method	Scope of Application
10	Ferrara, C., Migliaro, V., Ventura, F., & De Feo, G. (2023). An economic and environmental analysis of wine packaging systems in Italy: A life cycle (LC) approach. *Science of the Total Environment*, *857*, 159323. https://doi.org/10.1016/j.scitotenv.2022.159323	> Packaging > Sustainability > Wine LCA > LCC > Circular economy	Paper	LCC application	Food Packaging
11	Sazdovski, I., Bala, A., & Fullana-i-Palmer, P. (2021). Linking LCA literature with circular economy value creation: A review on beverage packaging. *Science of the Total Environment*, *771*, 145322. https://doi.org/10.1016/j.scitotenv.2021.145322	> Beverage packaging > Life Cycle Assessment (LCA) > End-of-life > Circular economy > Material quality > Recyclability	Review	LCA application	Food Packaging
12	Oki, Y. & Sasaki, H. (2000). Social and Environmental Impacts of Packaging (LCA and Assessment of Packaging Functions). *Packaging Technology and Science*, *13*(2), 45–53. https://doi.org/10.1002/1099-1522(200003/04)13:2<45::AID-PTS496>3.0.CO;2-#	> Packaging function > Environment > LCA > Sustainable	Paper	S-LCA application	Food Packaging
13	Kakadellis, S. & Harris, H. (2020). Don't scrap the waste: The need for broader system boundaries in bioplastic food packaging life-cycle assessment–A critical review. *Journal of Cleaner Production*, *274*, 122831. https://doi.org/10.1016/j.jclepro.2020.122831	> Bioplastic > Food waste > Life Cycle Assessment (LCA) > Plastic packaging > Systematic literature review > Waste management	Review	LCA application	Food Packaging
14	Silva, N. & Molina-Besch, K. (2023). Replacing plastic with corrugated cardboard: A carbon footprint analysis of disposable packaging in a B2B global supply chain–A case study. *Resources, Conservation and Recycling*, *191*, 106871. https://doi.org/10.1016/j.resconrec.2023.106871	> Cardboard > Carbon footprint > Case study > LCA > Packaging > Plastic	Paper	LCA application	Food Packaging

N.	Publication	Keywords	Type of publication	Assessment Method	Scope of Application
15	Kazancoglu, Y., Ada, E., Ozbiltekin-Pala, M., & As¸kın Uzel, R. (2023). In the nexus of sustainability, circular economy and food industry: Circular food package design. *Journal of Cleaner Production*, *415*, 137778. https://doi.org/10.1016/j.jclepro.2023.137778	> Food packaging design > Sustainability > Circular economy > Quality function deployment	Paper	LSCA method	Food Packaging
16	Siracusa, V., Ingrao, C., Lo Giudice, A., Mbohwa, C., & Dalla Rosa, M. (2014). Environmental assessment of a multilayer polymer bag for food packaging and preservation: An LCA approach. *Food Research International*, *62*, 151–161. http://dx.doi.org/10.1016/j.foodres.2014.02.010	> Life Cycle Assessment (LCA) > Environmental sustainability > Food packaging > Improvement hypothesis > Multilayer polymer film	Paper	LCA application	Food Packaging
17	Zabaniotou, A., & Kassidi, E. (2003). Life cycle assessment applied to egg packaging made from polystyrene and recycled paper. *Journal of Cleaner Production*, *11*(5), 549–559. https://doi.org/10.1016/S0959-6526(02)00076-8	> LCA > Egg packages > Recycled paper > Polystyrene	Paper	LCA application	Food Packaging
18	De Monte, M., Padoano, E. & Pozzetto, D. (2005). Alternative coffee packaging: an analysis from a life cycle point of view. *Journal of Food Engineering*, *66*(4), 405–411. https://doi.org/10.1016/j.jfoodeng.2004.04.006	> Environmental impact > LCA > Food packing	Paper	LCA application	Food Packaging
19	Gomes, T. S., Visconte, L. L. Y., & Pacheco, E. B. A. V. (2019). life cycle assessment of polyethylene terephthalate packaging: An overview. *Journal of Polymers and the Environment*, *27*(3), 533–548. https://doi.org/10.1007/s10924-019-01375-5	> Polyethylene terephthalate > PET > Life Cycle Assessment (LCA) > Recycling > Environmental impact	Review	LCA application	Food Packaging

N.	Publication	Keywords	Type of publication	Assessment Method	Scope of Application
20	Ada, E., Kazancoglu, Y., Gozacan-Chase, N., & Altin, O. (2023). Challenges for circular food packaging: Circular resources utilization. *Applied Food Research*, *3*(2), 100310. https://doi.org/10.1016/j.afres.2023.100310	> Circular economy > Sustainable packaging > Sustainable food supply chain > Food waste > Food packaging	Paper	LCA application	Food Packaging
21	Pfoser, S., Herman, K., Massimiani, A., Brandtner, P., & Schauer, O. (2022). From linear to circular packaging: Enablers and challenges in the fashion industry. In M. Freitag, A. Kinra, H. Kotzab, & N. Megow (Eds.), *Dynamics in Logistics* (pp. 435–445). Springer International Publishing. https://doi.org/10.1007/978-3-031-05359-7_35	> Circular economy > Sustainable packaging > e-commerce > Fashion industry > PESTEL analysis	Conference	LSCA method	Fashion Industry
22	Campbell, D. (2021). *Online Fashions overuse of unsustainable packaging: An exploration into the fashion industry's use of polybags*. University of Southampton.	> e-commerce > Fashion industry > Polybags	Report	LCA application	Fashion Industry
23	Zamani, B., Sandin, G., & Peters, G. M. (2017). Life cycle assessment of clothing libraries: Can collaborative consumption reduce the environmental impact of fast fashion? *Journal of Cleaner Production*, *162*, 1368–1375. https://doi.org/10.1016/j.jclepro.2017.06.128	> Problem shifting > Apparel > Climate change > Ecotoxicity > Eutrophication > Water use	Paper	LCA application	Fashion Industry
24	Enlund, E., & Nilsson, J. (2021). *Sustainable Decision-Making in the Fashion Industry. How to influence the fashion industry to adopt more sustainable packaging solutions*. KTH Industrial Engineering and Management.	> Fashion industry > Sustainability > Packaging > Drivers > Institutional logics > Barriers > Product developments > Decision-making > LCA > Platform > B2B	Thesis	LCA application	Fashion Industry

N.	Publication	Keywords	Type of publication	Assessment Method	Scope of Application
25	Park, J., & Waqar, Z. (2022). Life cycle assessment of returnable mailers used for apparel electronic commerce: A case study in Canada. *Packaging Technology and Science*, *35*(9), 651–662. https://doi.org/10.1002/pts.2653.	> E-commerce > Life cycle assessment > Packaging sustainability > Returnable packaging	Paper	LCA application	Fashion Industry

DIGITAL WASTE PASSPORT. DESIGN A CROSS-SECTORIAL PLATFORM OF SERVICES TO FACILITATE TEXTILE SMES OF MADE IN ITALY IN ACHIEVING TRACEABILITY AND CIRCULARITY

Debora Giorgi, Marco Bellandi**, Claudia Morea*, Chiara Rutigliano*, Luca Incrocci*, Matteo Bertelli*, Elizaveta Stark***

1. Introduction

The research addresses the need for SMEs in the textile and fashion industry, particularly those representing Made in Italy, to align with new European regulations on traceability and circularity. The research aims to propose an ecosystem of services to help SMEs remain competitive by promoting traceability at the End-of-Life stage and expanding cross-sectoral market opportunities for using recycled materials.

In particular, the **opportunities offered by the Digital Product Passport** and traceability technologies to support the transition to circular supply chain and recycling scenarios had been explored. The Digital Product Passport brings up new levels of traceability and transparency along the entire supply chain through the collection, classification, comparison, and transmission of data among all actors in the textile product life cycle, as required by European legislation. However, there are still open issues related to the textile waste traceability and its entry into new life cycles. Therefore, the main goal of the research is the creation of an ecosystem of services designed to support and guide clusters of SMEs, start-ups, and research centers in textile districts towards a circular and sustainable transition through cross-sectoral solutions. Key research areas include secondary materials, textile recycling technologies, regulations, and SME readiness for these changes. The project presented here provides the definition of a digital platform to support ecodesign in the textile sector starting from the integration and implementation of current digital tools for the textile and fashion industry.

**Department of Architecture, University of Florence, Italy*

***Department of Economics and Management, University of Florence, Italy*

2. Research framework and methodology

The research has been structured on three phases, the first explorative of specific topics, the second co-design phase characterized by stakeholders' involvement, and the third phase of infrastructure design and prototype in collaboration with Italtel spa.

In the first phase a State of Art related to four specific research topics was conducted, specifically: 1) New European regulation for a more sustainable textile industry, 2) technologies for traceability (DPP), 3) textile recycling technologies and machineries 4) cross-sectoral market opportunities 5) District and Circular Business Model.

For the State of the Art was conducted a Desk and Field research. The Desk research included: Literature Review, using tools such as Google Scholar and Scopus; Analysis of both sectoral and cross-sectoral markets; Analysis of regulations and directives regarding the project issues, including possible cross-sectoral applications, Innovative technologies, Stakeholders map and Ecosystem Map. The Field Research included: Meetings with key stakeholders (trade associations, informal networks, industry and technology companies, including startups, policy makers); participation in major industry events interviews; focus groups; company visits; questionnaires.

The outcomes of this phase were the identification of gaps between regulations and companies' needs, the Mapping of the stakeholders Ecosystem around the topic at local level (Prato Textile District) and a Concept proposition for services platform.

The second phase had the intention to verify with the possible stakeholders the gaps and needs identified and validate the platform concept with the proposition of a service ecosystem service for the Prato District. The research involved the participation of various stakeholders operating in the textile industry at regional level in a co-design workshop, preceded by preliminary interviews, questionnaires, and company visits.

This collaborative approach allowed to highlight cross-sectoral opportunities, bringing together diverse expertise and activating collaborations across the entire supply chain: a co-design process brought together stakeholders from various parts of the value chain, including manufacturers, recyclers, technology and machineries suppliers, industry associations. The applica-

tion of co-design methodologies facilitated the identification of opportunities that may not be apparent from a single perspective (Pirinen, 2016). Furthermore, from the stakeholders' in-depth knowledge of production processes, innovative solutions emerged, leading to further collaborations and requests for the definition of tailored tools. For example, a technology supplier could collaborate with a recycler to develop a new method for identifying the composition of mixed material blends, facilitating more effective recycling (Tukker, 2015).

Based on the outcomes of the previous two phases, the third phase concerned the experimental design of a services infrastructure aimed at supporting clusters of SMEs. Specifically, three specific objectives were identified and prioritized in order of importance in relation to the setup of the services infrastructure:

- To support companies in the data collection of waste—secondary raw materials;
- To promote digital and accessible sectoral specific tools for traceability and ecodesign;
- To facilitate a network creation based on sectoral and cross-sectoral recycling opportunities.

Methodologies from Service Design, UI/UX Design were applied.

3. Results discussion

3.1. European Regulation for textile recycling

Annually, the EU discards 5.8 million tonnes of textiles, averaging 11 kg per person, while globally, a truckload of textiles is incinerated or discarded every second (Kew, 2023). To mitigate this, EU's Green Deal, Circular Economy Action Plan, and Industrial Strategy prioritize the textile sector for reducing environmental impacts. Moreover, the Strategy for Sustainable and Circular Textiles envisions an industry producing durable, recyclable, and non-toxic products by 2030.

Mandatory textile waste collection across Europe from 2025 presents both challenges and opportunities, particularly in recycling mixed fibers like wool-polyester. Additionally, the prolif-

eration of certification schemes has generated confusion, often leading to misleading sustainability claims.

In response, EURATEX proposed European Textile Recycling Hubs (ReHubs) to align with EU circular economy goals by processing large volumes of textile waste and fostering industrial symbiosis, though concerns about material quality and data accuracy persist. While concerns have been raised regarding the low quality of output materials and insufficient data on input materials, ReHubs have the potential to lower waste management costs, enhance industry collaboration, and foster employment.

The revision of the Waste Framework Directive seeks to standardize Extended Producer Responsibility (EPR) for textiles, ensuring producers manage post-consumer waste. With 25-40% of textiles discarded during manufacturing and less than 1% reused, textile recycling in the EU remains limited, with only 20% of materials downcycled (JRC, 2021). The 2023 update to the REACH directive introduces sustainability criteria for chemicals used in textile production. Enhanced traceability technologies are needed to preserve the quality of secondary raw materials and increase cross-sector market opportunities.

3.2. Technology for circularity

Traceability technologies like blockchain can improve supply chain transparency, and the proposed Ecodesign Directive amendment encourages their adoption, despite cost and regulatory challenges. Directive 2024/825/EU, set for September 2026, aims to combat greenwashing by banning invalid certifications. Effective communication across supply chains, from production to recycling and reuse, is crucial for sustainability.

Digitalization is key to achieving circular supply chains, with major brands adopting technologies to share product data. However, concerns remain about regulation, privacy, and affordability, especially for SMEs. The Ecodesign for Sustainable Products Regulation (ESPR) introduces the Digital Product Passport (DPP), requiring public disclosure of product circularity and ecodesign data. DPPs could provide information on material composition, production processes, and ownership history, aiding regulatory compliance and informed consumer decisions. These tools are pivotal for enhancing product durability, recyclability, and transparency in the fashion industry.

However, integrating DPPs into secondary raw materials remains a challenge. Two prominent issues that arose here: a) textile industry's global and complex value chain, which is heavily reliant on outsourcing and often lacks transparency; b) pressure from consumer groups, regulations, and other stakeholders are driving technological improvements.

Our research explores the integration of digital solutions for sharing crucial information related to recycling, reuse, repair, and disassembly data throughout the supply chain, focusing on textile waste traceability and management. It examines enabling technologies like Blockchain, IoT, DPPs, and Digital Twins, with a particular focus on identifying mandatory and optional data for DPP implementation.

The research highlighted persisting challenges, especially for SMEs, which face excessive costs, long payback periods, and regulatory uncertainty. While large companies can invest in these technologies, SMEs struggle with the complexities of data sharing. Despite these challenges, DPPs offer significant potential for SMEs by helping them comply with traceability regulations, enhance their reputation, and access circular economy markets. Finally, effective DPP integration could improve the eco-design.

Current DPP initiatives lack unified standards, and different sectors, like battery recycling, complicate the landscape further. It remains unclear whether a single document or multiple passports will be required for the same product. Success will depend on ensuring a) data security and trust; b) technologies accessibility to SMEs; c) fostering stakeholder collaboration to develop standardized protocols.

3.3. Textile recycling types and cross-sectoral opportunities

End-of-life textile treatment is divided into pre-consumer and post-consumer waste. Pre-consumer waste, generated during production (e.g., offcuts, fibers), is classified in the European Waste Catalogue (CER, 2013). Recycling multi-material fiber blends, especially those containing elastane, is technically challenging and requires advanced technologies like AI, Near-Infrared Spectroscopy, and thermo-chemical processes. Non-reusable textiles often end up exported and incinerated in landfills.

Effective management involves optimizing production to reduce material use through centralized collection, waste analysis, and machinery adjustments.

Mechanical recycling is the most common method, though it often requires blending with virgin materials. Chemical and biochemical recycling methods (e.g., feedstock, enzymatic processes) offer potential but face environmental and adoption hurdles. Simpler methods, like composting and converting textiles into cleaning rags, offer limited sustainability benefits.

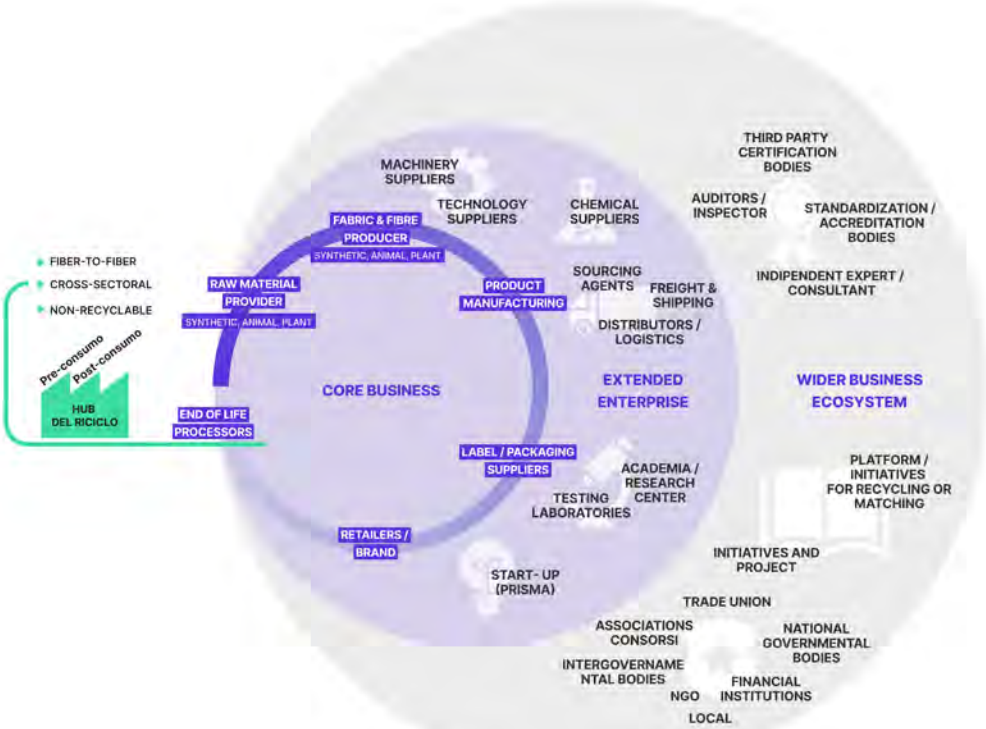
Recycled textiles are used in industries such as automotive, construction, and packaging, necessitating cross-sector collaboration and regulatory adherence. However, meeting diverse industry standards remains a challenge, prompting the development of complex assessment scales for recycled product feasibility across sectors. Regions like Prato excel in mechanical recycling, processing up to 36,000 tons annually, though challenges such as chemical contamination and meeting regulatory standards persist.

The complexity of textile recycling highlights the need for advanced technologies and improved regulatory frameworks. Digital tools, such as the Digital Product Passport, can enhance material traceability, regulatory compliance, and sustainability in the textile industry.

3.4. Textile-clothing districts and Circular Business Models

Europe, particularly Italy, has a rich history in the textile and clothing industries, shaped by the development of specialized clusters in defined local areas. These clusters comprise networks of firms engaged in related stages of value chains, supported by complementary services and institutions. In Italy, some clusters are led by large firms, while others consist solely of SMEs, such as the renowned Prato district (Dei Ottati, 2009).

Italian textile-clothing SME clusters thrived in the late 19th century due to a combination of: a) networked industrial efficiency (economies of specialization among networks of SMEs); b) artisanal care preserved in some SMEs (enhancing quality, image, and variety of products); c) and the supporting role of socio-cultural and institutional relations embedded in the place (collective infrastructures and trust-based relations, industrial atmosphere for growing human capital and entrepreneurship, collective pro-



1. Ecosystem Map of the textile district, with the proposition of the Recycling Hub as platform manager.
All images are reproduced in color in the online edition of the book.

cesses of creativity) (Becattini, 2004). Despite facing challenges related to environmental sustainability, these clusters have managed issues like waste and water management through collective investments (Bellandi et al., 2021). Prato, for example, has a long-standing tradition of wool recycling, which has become a foundation for Circular Business Models (CBMs).

CBMs focus on reducing energy consumption and waste, integrating strategies like reuse, recycling, and product longevity. In the textile industry, three types of CBMs—"more use per user," "more users per product," and "beyond the physical product"—have been identified (Ellen MacArthur Foundation, 2021). However, CBMs face difficulties in competing with the dominant linear, growth-oriented models, such as fast fashion, which offer cheaper short-term solutions, like exporting waste (Buchel et al., 2022). SMEs, though well-positioned to drive CBM innovation due to their sensitivity to social and environmental contexts, often struggle with limited resources for innovation and coordination. Effective CBMs require cooperation along value chains where SMEs might compete. Platforms and districts play a crucial role in providing services that help SMEs explore ecodesign and navigate coordinated CBMs. Districts, such as Prato, function as open laboratories where SMEs can adapt to the cultural, technological, and organizational changes needed to embrace CBMs (Bellandi & Storai, 2022).

The following sections will discuss the development of a cross-sector platform for traceability and circularity services for textile SMEs, highlighting the opportunities and challenges faced by platforms and district-based SME clusters.

4. From the concept to the prototype

The Desk and Field research identified four key areas of focus:

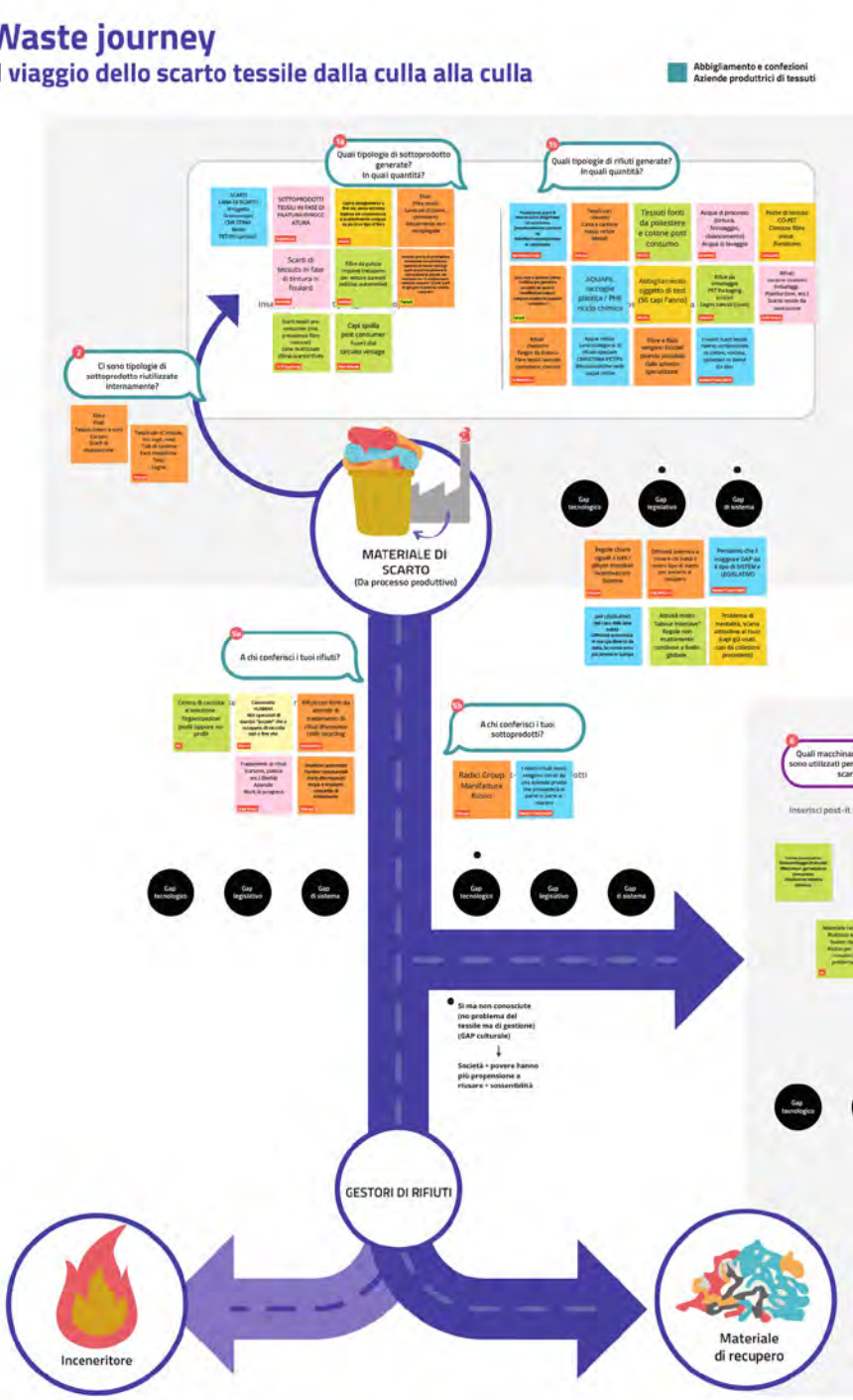
- Law & Regulations: lack of clarity exists in regulations concerning textile waste, recovery of exported materials, and reuse of recycled products in other sectors, hindering their certification and market competitiveness;
- Circular Network: absence of local waste supply chains to reduce dependence on secondary raw materials from

abroad, along with inadequate solutions for processing and valorising textile waste;
- Circular Products & Materials: The cross-sectoral application of recycled materials is limited by a lack of awareness of their potential and regulatory barriers, affecting market competitiveness. However, transforming waste into a resource could unlock new competitive market opportunities;
- Technologies and Digital Platforms: The implementation of tracking systems for pre- and post-consumer products is necessary to ensure transparency and compliance with European regulations. Potential integration of AI, LCA, and tracking systems is also explored.

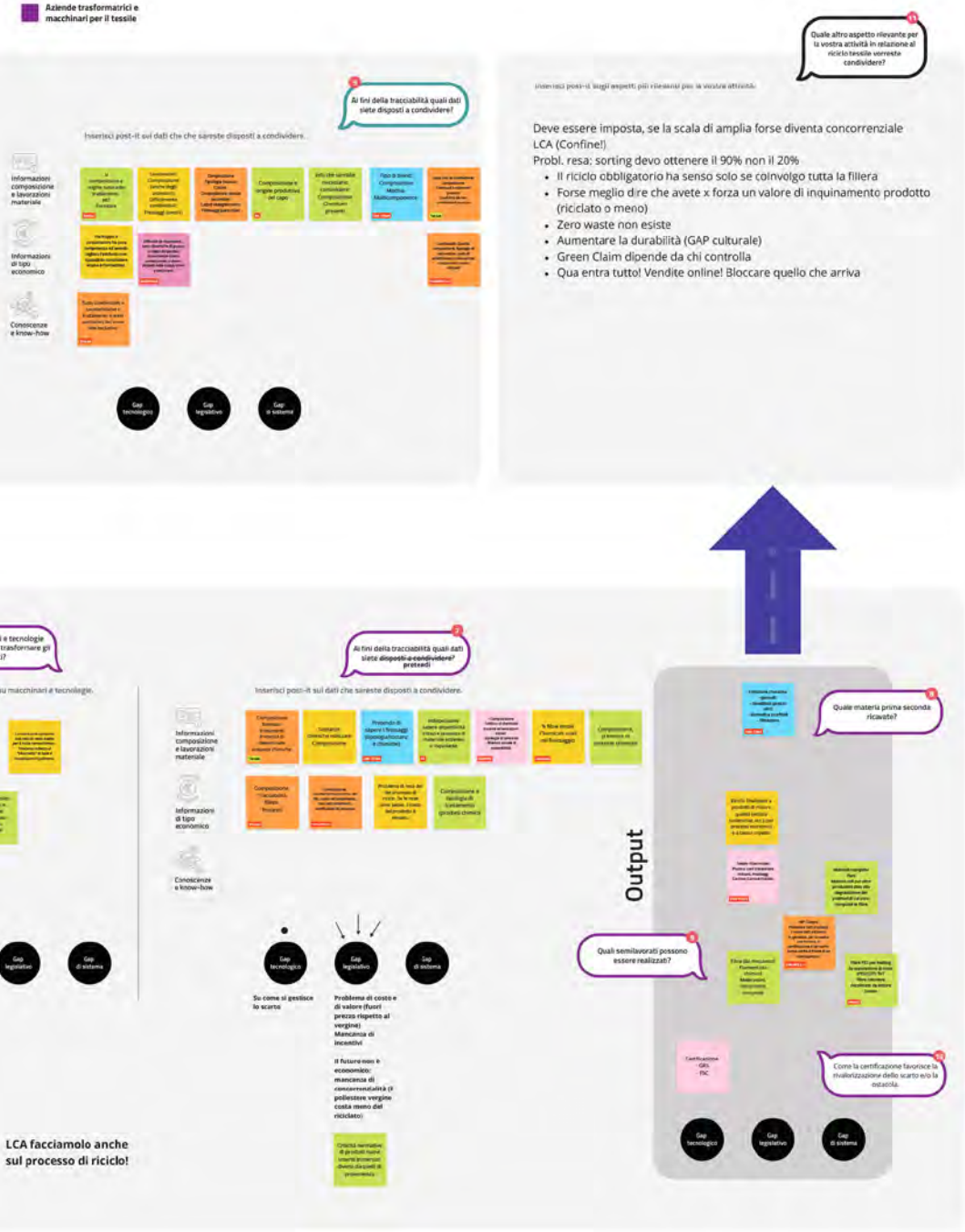
The research then focused on designing a range of services to address these identified gaps and offered by web-platform. Moreover to validate the platform's service offerings, a co-design process was conducted with stakeholders from the Prato District and Biella District (fig. 2). This process included the use of card games to encourage dialogue around proposed solutions. The initiative was informed by data from field research (literature review and best practices) and desk analysis (stakeholder analysis and recycling scenarios). The co-design approach was structured to engage stakeholders in defining long-term goals and identifying conditions necessary to achieve them, aiding in the planning and evaluation of project ideas. Key opportunities for the platform were identified in two areas: the creation of a database to connect companies via cross-sector case studies, and the development of tools for SMEs to collect technical data for improving traceability and ecodesign of pre- and post-consumer textiles. These traceability requirements for semi-finished and recycled textiles are aligned with Digital Product Passport legislation and analysis of online databases.

4.1. Designing the "Cross-sectoral Platform"

The proposed strategy adopts an integrated approach, connecting textile companies with those in other sectors to drive local cross-sectoral development. This fosters a circular and sustainable approach that addresses waste while creating growth opportunities for Made in Italy companies through innovation, diversification, and local resource enhancement. The service



2. Tool and output from the co-design activity related to the second phase of the research project.


Aziende trasformatrici e macchinari per il tessile
Ai fini della tracciabilità quali dati siete disposti a condividere?
Inserisci post-it sui dati che sareste disposti a condividere.
Informazioni composizione e lavorazioni materiale
Informazioni di tipo economico
Conoscenze e know-how
Gap tecnologico
Gap legislativo
Gap di sistema
Quale altro aspetto rilevante per la vostra attività in relazione al riciclo tessile vorreste condividere?
Deve essere imposta, se la scala di amplia forse diventa concorrenziale
LCA (Confine!)
Probl. resa: sorting devo ottenere il 90% non il 20%
Il riciclo obbligatorio ha senso solo se coinvolgo tutta la filiera
Forse meglio dire che avete x forza un valore di inquinamento prodotto (riciclato o meno)
Zero waste non esiste
Aumentare la durabilità (GAP culturale)
Green Claim dipende da chi controlla
Qua entra tutto! Vendite online! Bloccare quello che arriva
Output
Quale materia prima seconda ricavate?
Quali semilavorati possono essere realizzati?
Come la certificazione favorisce la rivalorizzazione dello scarto e/o la materia.
Su come si gestisce lo scarto
Problema di costo e di valore (fuori prezzo rispetto al vergine)
Mancanza di incentivi
Il futuro non è economico:
mancanza di concorrenzialità (il poliestere vergine costa meno del riciclato)
LCA facciamolo anche sul processo di riciclo!

platform envisions a world where companies access sustainability expertise and collaborate to promote sustainable development. The platform's mission is to support the transition to circular and cross-sectoral business models, promoting ecodesign through the reuse of textile waste. It aims to drive global change by creating local synergies and fostering collaboration among stakeholders.

The platform is then designed for collaboration, allowing users to share content based on their role in the ecosystem, which can evolve with market opportunities (fig. 3). The platform is organised into three sections:

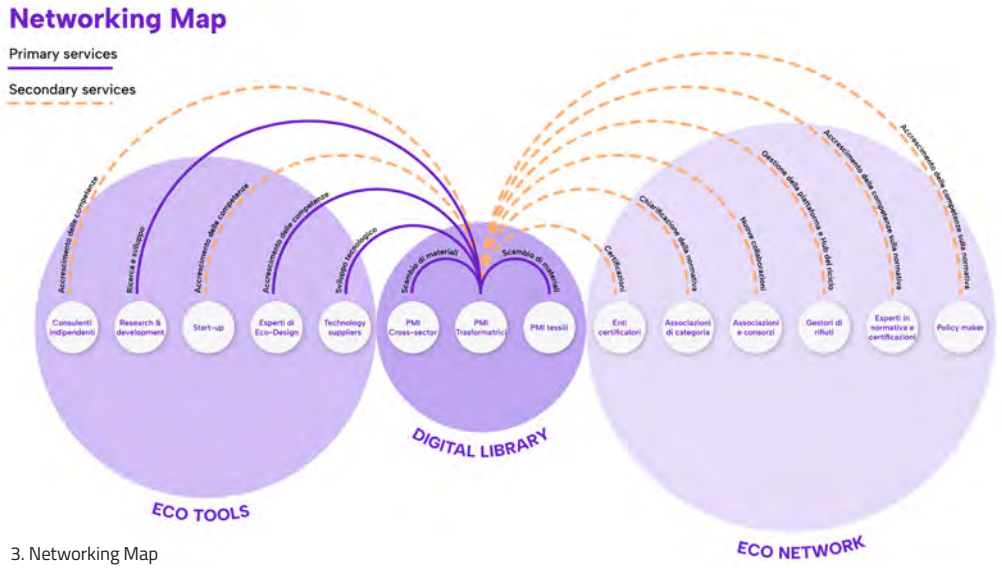
- Digitalibrary: The core section, facilitating the cross-sectoral reuse of pre-consumer textile waste through a secure traceability system (Digital Waste Passport) and a certified marketplace;
- Eco-toolkit: Provides SMEs with access to ecodesign tools, calculation software (e.g., LCA), best practices, and consulting services on sustainability and regulations;
- Eco-network: Enhances sectoral and cross-sectoral networking through features like social walls, challenges, and interactive infographics to increase engagement.

From the State-of-Art on the four topics discussed above, it was possible to proceed with mapping of the platform stakeholders, as well as organizing them by areas of platform interaction within the textile supply chain. Finally a Stakeholders Map was organized into Primary, Secondary and Indirect stakeholders.

Those stakeholders were analyzed and arranged into an Ecosystem Map (fig. 2), through the lens of the product end-of-life cycle. Finally, three layers were highlighted in the Ecosystem of the Prato Textile District: a **"core business"** layer, an **"extended enterprises"** layer and a **"wider business"** layer.

The ecosystem map built on the three layers sets a clear overview of the stakeholders already involved in the textile value-chain and offers a wider overview of the opportunities of involvement.

User research, including interviews, surveys, and site visits, explored the technological and circular capabilities of 224 companies, identifying service needs in areas such as LCA, ecode-



3. Networking Map of the Cross-sectorial Platform. The map shows the interactions between the users and three platform sections: Digital Waste Library, Eco-tool, Eco Networking.

sign, traceability, waste treatment, and digitalization. Co-design sessions engaged potential stakeholders to address specific challenges. The target users of the platform include textile and fashion SMEs, waste management firms, recycling technology producers, sustainability experts, and trade associations.

Then six archetype users (personas) were developed, including a wool-yarn producer, garment manufacturer, textile waste processor, start-up, sustainability consultant, and association president. These personas helped define the platform's architecture and usability, considering each user's digitalization level, sustainability awareness, frustrations, and needs, and aligning them with platform solutions.

4.2. Digital Waste Passport Prototype

Through the partnership in the MICS project of Italtel spa, it has been possible to go forward the design phase and start the prototype of the cross-sectoral Platform. The Digital Waste Passport (DWP) was selected as the prototype's foundation, serving as the core functionality of the web platform and a key competitive advantage.

The DWP generates verified information regarding waste materials through blockchain technology, enabling users to of-

fer second-life opportunities for textile waste while providing a secure marketplace for others to acquire pre-consumer secondary raw materials. This functionality is essential for facilitating the circularity of textiles within sectoral and cross-sectoral contexts.

In response to the current absence of a Digital Product Passport, the DWP was constructed based on the sustainability data required in various contexts, focusing on information pertinent to Life Cycle Assessment (LCA), ecolabels, and supply chain traceability and transparency. These data were organized through a blockchain technology to ensure a validity of data and generate a safe and controlled market.

Ongoing actions aim to preliminarily define the Digital Product Passport by mapping the requirements necessary for developing tools that meet stakeholder interests. This will follow the realisation of a mock-up and the validation with preselected stakeholders.

With the purpose to achieve a preliminary definition of DPP, a set of actions are ongoing. Actions are oriented to provide a first mapping of the requirements necessary to define an architecture that satisfies the development of tools of interest to stakeholders, not yet defined, following the completion of the state-of-the-art document. Prerequisites: Study of tasks defined by the proponent to determine the role and activities under Italtel expertise.

5. Conclusion

The proposed intervention aims to address the critical need for sustainable solutions within an uncertain and evolving regulatory framework. This uncertainty complicates the authorization processes necessary for cross-sectoral collaboration and the reuse of secondary raw materials. Key barriers include high investment costs, long payback periods, and regulatory uncertainties.

The introduction of the Digital Product Passport (DPP) in the textile sector promises transformation but is currently slow and fragmented, lacking a unified framework. While DPP schemes exist in other sectors, their impact on textiles remains

uncertain, and it is unclear whether a single or multiple passports will be established for products.

The research here presented, and its web platform output aims to fill the gap between regulation goals and companies capabilities. The Digital Waste Passport designed from this research aims to show one of the workable solutions to facilitate the End-of-life process and finally achieve circularity in the textile supply chain. Moreover, new collaborative services are needed to help SMEs join the circular supply chain and ecodesign opportunities. To facilitate this transition, the design of service platform would be crucial for SMEs and industrial designers, providing clarity on traceability regulations and promoting the reuse of pre-consumer waste as a resource. Strengthening local capacities and fostering collaboration between public and private entities will enhance the textile production chain through a cross-sectoral approach, contributing to economic growth and sustainability.

Acknowledgement

This contribution was shared and agreed between the authors in content and conclusions. Specifically Marco Bellandi edited paragraph 3.4.

References

Methodology

Meroni & Sangiorgi, 2011
Meroni, A., & Sangiorgi, D. (2011), *Design for services*, Routledge.

Sangiorgi & Prendiville, 2017
Sangiorgi, D., & Prendiville, A. (2017). *Designing for service. Key issues and new directions*. Bloomsbury.

Taplin & Clark, 2012
Taplin, D. H., & Clark, H. (2012). *Theory of change basic*, ActKnowledge.

Tassi, 2019
Tassi R., 2019, *Service Designer. Il progettista alle prese con sistemi complessi*, Franco Angeli.

Zannoni, 2018
Zannoni, M. (2018). *Progetto e interazione: il design degli ecosistemi interattivi*, Quodlibet.

Textile Districts and Clusters

Becattini, 2004
Becattini, G. (2004). *Industrial Districts: A new approach to industrial change*, Edward Elgar Publishing.

Bellandi et al., 2021
Bellandi, M., Ruiz-Fuensanta, M. J., & Santini, E. (2021). Factors of environmental sustainability in italian industrial districts: A composite environmental sustainability index. In S. R. Sedita & S. Blasi (Eds.), *Rethinking Clusters. Place-based Value Creation in Sustainability Transitions* (pp. 111–124). Springer.

Bellandi & Storai, 2022
Bellandi, M., & Storai, D. (2022). Structural change and agency in territorial development: The case of mature industrial districts. *Regional Studies*, 1–13. https://doi.org/10.1080/00343404.2022.2107190

Buchel et al., 2022
Buchel, S., Hebinck, A., Lavanga, M., & Loorbach, D. (2022). Disrupting the status quo: a sustainability transitions analysis of the fashion system. *Sustainability: Science, Practice and Policy*, *18*(1), 231–246. https://doi.org/10.1080/15487733.2022.2040231

Dei Ottati, 2009
Dei Ottati, G. (2009). An industrial district facing the challenges of globalization: Prato today. *European Planning Studies*, *17*(12), 1817–1835.

Ellen MacArthur Foundation, 2021
Ellen MacArthur Foundation. (2021). *Circular business models: Redefining growth for a thriving fashion industry*. https://ellenmacarthurfoundation.org/fashion-business-models/overview

Le Feber & Smit, 2023
Le Feber, N., & Smit, M. J. (2023). Fashion companies pioneering with eco-innovations in the Swedish fashion industry: Motivations, resources, and co-operation. *Circular Economy and Sustainability*, *3*(5), 1885–1905. https://doi.org/10.1007/s43615-022-00246-x

End of Life: recycling scenarios

EconomiaCircolare.com, 2022
EconomiaCircolare.com (Ed.). (2022). *Sfide per un tessile circolare. Dall'ecodesign alla seconda vita dei materiali* (I quaderni di EconomiaCircolare.com), Centro Documentazione Conflitti Ambientali CDCA.

Eisenreich, Füller & Stuchtey, 2021
Eisenreich, A., Füller, J. & Stuchtey, M. (2021). Opencircular innovation – How companies can develop circular innovations in collaboration with stakeholders. *Sustainability*, *13*(23), 1–23. https://doi.org/10.3390/su132313456

Eppinger, 2022
Eppinger, E. (2022). Recycling technologies for enabling sustainability transitions of the fashion industry: status quo and avenues for increasing post-consumer waste recycling. *Sustainability: Science, Practice and Policy*, *18*(1), 114–128. https://doi.org/10.1080/15487733.2022.2027122

European Commission, 2020
European Commission. (2020). *A new circular economy action plan for a cleaner and more competitive Europe*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0098

European Commission, 2022
European Commission. (2022). *Strategia dell'UE per prodotti tessili sostenibili e circolari*. Comunicazione della Commissione al Parlamento Europeo, al Consiglio, al Comitato economico e Sociale europeo e al Comitato delle Regioni. https://www.europarl.europa.eu/doceo/document/TA-9-2023-0215_IT.html

European Commission, 2023
European Commission. (2023). *Proposal for a targeted revision of the Waste Framework Directive*. https://environment.ec.europa.eu/publications/proposal-targeted-revision-waste-framework-directive_en

European Commission et al., 2021
European Commission: Directorate-general for internal market, industry, entrepreneurship and SMEs, Duhoux, T., Maes, E., Hirschnitz-Garbers, M., Peeters, K., Asscherickx, L., Christis, M., & Sachdeva, A. (2021). *Study on the technical, regulatory, economic and environmental effectiveness of textile fibres recycling*, *Final report*. Publications Office. https://data.europa.eu/doi/10.2873/828412

European Environmental Agency, 2023
European Environmental Agency. (2023). *EU exports of used textiles in Europe's circular economy*. https://www.eea.europa.eu/publications/eu-exports-of-used-textiles

European Fashion Alliance (EFA), 2023
European Fashion Alliance (EFA). (2023). *EFA Positioning on ecodesign for sustainable products regulation*. www.europeanfashionalliance.org

Fashion For Good, 2022a
Fashion For Good. (2022a). *Sorting for circularity Europe. Sorters handbook: How to conduct a sorting analysis using Hand-Held near Infrared Scanning Technology*. https://reports.fashionforgood.com/wp-content/uploads/2022/09/Sorting-For-Circularity-Europe_Sorters-Handbook_Fashion-for-Good.pdf

Fashion For Good, 2022b
Fashion for Good. (2022b). *Sorting for circularity europe. An evaluation and commercial assessment of textile waste across Europe*. https://reports.fashionforgood.com/report/sorting-for-circularity-europe/

Fondazione per lo Sviluppo Sostenibile & Fise Unicircular, 2021
Fondazione per lo Sviluppo Sostenibile & Fise Unicircular (Eds.) (2021). *Italia del Riciclo*. Fondazione per lo Sviluppo Sostenibile.

ISPRA, 2021
ISPRA. (2021). *Rapporto rifiuti urbani 2021* (dati 2020).

Köhler et al., 2021
Köhler, A., Watson, D., Trzepacz, S., Löw, C., Liu, R., Danneck, J., … & Faraca,

G. (2021). *Circular economy perspectives in the EU textile sector*. Publications Office of the European Union.

Levänen et al., 2021
Levänen, J., Uusitalo, V., Härri, A., Kareinen, E., & Linnanen, L. (2021). Innovative recycling or extended use? Comparing the global warming potential of different ownership and end-of-life scenarios for textiles. *Environmental Research Letters*, *16*(5), 054069.

Ljungkvist, Watson & Elander, 2018
Ljungkvist, H., Watson, D. & Elander, M. (2018), *Developments in global markets for used textiles and implications for reuse and recycling*, Mistra Future Fashion.

Menci et al., 2007
Menci, A., Miraglino, P., Pieri, L., Piscitelli, C., & Ponzecchi, F. (2007). *I processi produttivi e di supporto del sistema tessile-abbigliamento a Prato. Analisi dei processi e delle figure chiave del settore*. Tipografia La Marina.

McKinsey & Company, 2022
McKinsey & Company. (2022). *Scaling textile recycling in Europe-turning waste into value*. McKinsey & Company. https://www.mckinsey.com/industries/retail/our-insights/scaling-textile-recycling-in-europe-turning-waste-into-value

Textile Exchange, 2022
Textile Exchange. (2022). *GRS-202. Guide to Recycled Inputs*. https://textileexchange.org/knowledge-center/documents/textile-exchange-guide-to-recycled-inputs/

United Nations Economic Commission for Europe (UNECE), 2021
United Nations Economic Commission for Europe (UNECE). (2021). *Recommendation No. 46: Enhancing Traceability and Transparency of Sustainable Value Chains in the Garment and Footwear Sector*. UNECE.

Wielechowski, Cozzolino & Layden, 2023
Wielechowski, R., Cozzolino, G., & Layden, A. (2023), *Following the thread*. Planet Tracker.

PROCESSES FOR MANAGING AND DESIGNING CIRCULARITY IN THE ITALIAN FURNITURE INDUSTRY. CURRENT PRACTICES AND FUTURE STRATEGIES FOR TOOLS OF INTERCONNECTIVITY

Lorenzo Imbesi, Sabrina Lucibello*, Emanuele Panizzi**, Serena Baiani*, Viktor Malakuczi*, Paola Altamura*, Luca D'Elia*, Carmen Rotondi*, Mariia Ershova*, Gabriele Rossini**

1. Background

The European furniture industry is undergoing a shift towards a circular economy, highlighting both its economic importance and environmental challenges (Farahmand & Rahimiaghdas, 2024). Despite a growing awareness of circular economy principles, the industry's adoption of circular practices, especially in reuse and recycling, remains limited. This is compounded by the minimal use of certifications for processes and products. Furniture waste in the EU constitutes over 4% of the total municipal solid waste, with 80% to 90% of it being incinerated or landfilled, and only about 10% recycled (Arditi, 2017). The traditional linear economy often leads to waste, where materials reach the end of their life cycle without further use. However, at the European level, research suggests that a circular economy framework (Pieroni et al., 2019) offers potential opportunities for increased efficiency and productivity in the furniture sector (Kirchherr & Piscicelli, 2019; Potting et al., 2017).

While circular strategies and practices focus on design approaches that retain resources in use and minimize waste (Murray et al., 2023), this shift requires advancement as much in the production systems (Bakker et al., 2014), as in products and services design and development tools (Moreno et al., 2016), aligned with the creation of updated organizational capabilities such as experimentation, value chain innovation, and human factors (Nilsson-Lindén et al., 2019). Adopting a circular design approach implies the creation of viable and sustainable alternative resource streams and competencies, establishing data hierarchies for waste prevention. This aligns with the European Commission's waste management directives (EU Commission, 2020), which view waste as a valuable resource to be reintroduced into the life cycle.

**Department of Planning, Design, Technology of Architecture, Sapienza University of Rome, Italy*

***Department of Computer Science, Sapienza University of Rome, Italy*

This contribution is based on the research project titled *From waste to manufacturing: digital tools to establish virtuous cycles*, which aims to promote the circular use of materials in the Italian furniture industry by facilitating the connection between three categories of stakeholders: Product Designers, Waste Producers (providing secondary raw materials or by-products), and Furniture Manufacturers who could directly utilize these circular materials. The research examines organizational models and experiments with advanced digital tools to help design circular materials and manage circular material flows among the identified categories of stakeholders.

2. Stakeholder mapping

The Research started with the analysis of existing regulations and identified processes that generate specific waste materials by screening ATECO codes,[1] which classify economic activities in Italy. These codes are crucial for determining businesses' eligibility for tax benefits, eco-incentives, and compliance with sustainability requirements.[2] The Research identified 56 ATECO codes linked to 487 different industries, focusing on sectors relevant to waste management. The Italian recycling supply chain includes 4,800 companies, with 70% primarily focused on waste recycling (ATECO 38, 39, 46.7) and 30% from the manufacturing sector, generating a significant economic impact of €10.5 billion and employing over 236,000 people. The Research also considered specialized consortia involved in recycling specific waste streams, which play a vital role in intermediate recycling activities, such as material sorting, that designers can leverage for creating new products, reducing disposal, and enhancing sustainability.

For the analysis of Waste Producers, the Research focused on companies associated with the ATECO code 38.32, which covers "Collection and sorting of materials." Specifically, the focus was on sectors dealing with metals, plastics, biomass, and unclassified urban waste. A total of 113 companies were identified, with 40 selected based on financial performance, ensuring project continuity. Similarly, the Research identified 45 ATECO codes related to the manufacturing sector, particularly within the Ital-

ian fashion and furniture industries. These codes were investigated to their smallest subcategories, identifying top companies at the national level and within the Lazio region. In total, 374 companies were identified as potentially interesting, with 141 located in Lazio, which is strategic for managing workflow and establishing strong relationships among participants in the project's early stages.

Concerning the Designers, the Research prioritized professionals already integrated into the production chains of these companies to ensure seamless collaboration and proactive engagement. Additionally, eight ATECO codes covering consultancy agencies and research were identified as potential external participants in the project's experimentation phase.

3. Field research methodology

The qualitative research phase involves adapting methods to ensure timely and relevant data collection across various disciplinary settings (Vindrola-Padros & Johnson, 2020). This phase includes semi-structured interviews to delve deeper into the information retrieved during the desk research phase (Safdar et al., 2021). Semi-structured interviews provide valuable insights and perspectives from individuals involved in the research area.

The qualitative analysis of the responses according to the project-grounded methodological approach (Corbin & Strauss, 2008) provides initial insights into the common knowledge base producers and manufacturers have about waste management within the Made in Italy production chain. Through a qualitative analysis of interviews conducted with key stakeholders, the project aimed to shed light on the prevailing attitudes and strategies towards sustainability and waste management in one of Italy's most celebrated sectors.

Following the identification of the most interested and interesting players, an interview campaign was conducted with each of them. The semi-structured interviews lasted approximately one hour each, and aimed at retrieving a clear picture of the type of activities of each interviewee by categorizing the information into seven clusters: 1) identity, 2) asset, 3)

network, 4) policies, 5) process, 6) tools and 7) waste management.

A first brief introduction of the company defines the identity (cluster 1) of the company, which usually evolves along with productions and opportunities offered by networks consolidated over time and the wealth of the company. The description introduced the asset (2) which defines the company's framework, often also defined by the bylaws, but qualifying the activity. One of the most relevant elements for the company has been also identified in their networking activities (3), defining the openness and extension of the business, best defining the possible interactions that can be built over the project, and the capability of the company to face the challenges of increasing complexities. Therefore, this cluster introduced the policies (4) that rule this network, as it is consequently relevant to give a clearer idea of the organizational structures. Ultimately, this understanding gives the Research the possibility to consider whether or not it would be possible to discuss the Open Innovation context.

The interviews moved then to the inner processes (5) of the company, as one of the aspects that most succinctly characterizes the company, defining its efficiency, quality, and control of production chains. It distinguishes not only for each interviewee (whether it was a Waste Producer or a Manufacturer) but also internally, where extremely heterogeneous and characteristic processes can be identified. Subsequently, the companies were more agile in introducing their tools (6) which, in the interview, were responsible for pushing the responders to discuss and distinguish between physical machinery and digital tools. As each individual within their own "production chain" adopts one or more tools to varying degrees, these elements represent one of the most peculiar indicators for the development of the Research, particularly when related to the digitization process. Lastly, the interviews were structured to investigate the waste management (7) capabilities of the responders, directly referring to the Manufacturers' awareness of waste control, the Producers' ability to link their EWC to specific production sectors (which could potentially lead to the direct correlation with the aforementioned ATECO), and finally, the LCA control of designers.

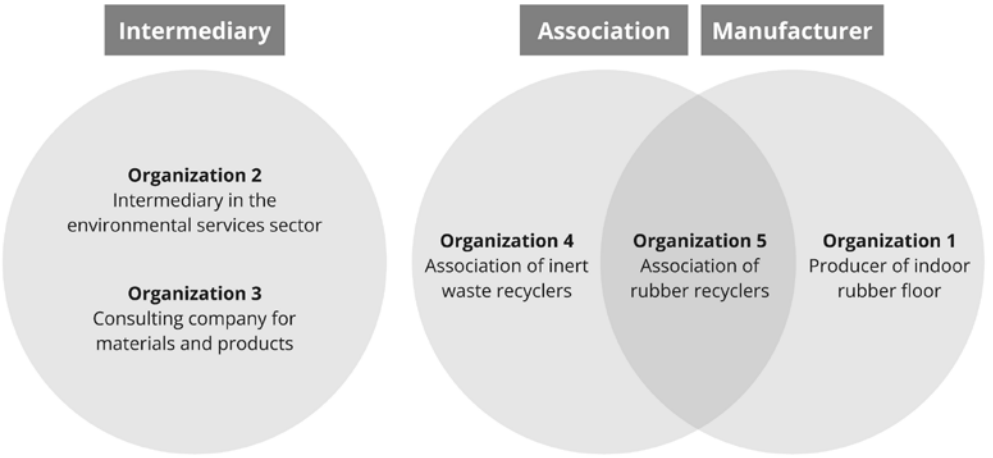
4. Participant Organizations: roles and positions

The research covers different types of stakeholders included in the process, with a total of five organizations that participated in the focus groups and interviews:

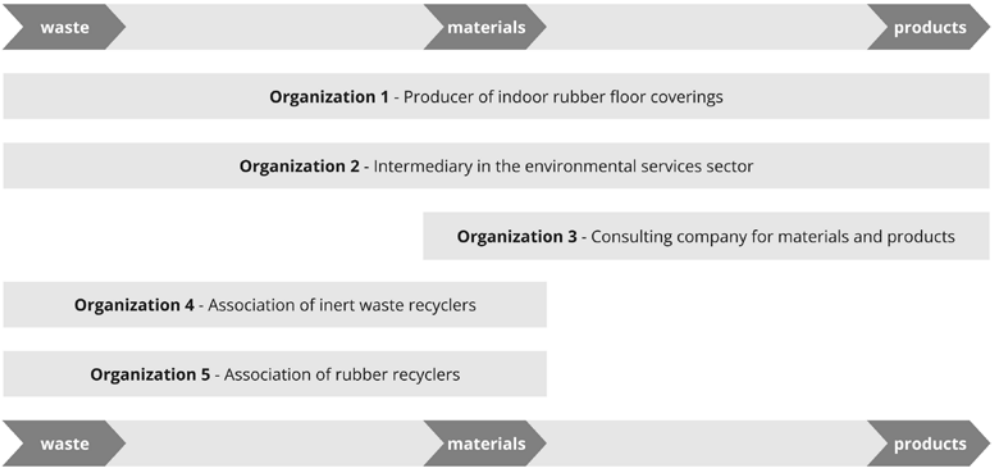
- Organization 1 is a producer of indoor rubber floor coverings, which are mainly used in public buildings and private facilities (ATECO code: 22.19.09 Manufacturer of other rubber products);
- Organization 2 is an intermediary in the environmental services sector that combines operational services with technical and scientific advice to reduce the environmental impact of its clients (ATECO code: 39.00.09 Other remediation activities and other waste management services);
- Organization 3 is a consulting and research company, specializing in the sustainability of materials and products, and in defining metrics for measuring the circular economy (ATECO code 74.9: Other professional, scientific and technical activities);
- Organization 4 is a trade association that represents and defends the interests of inert waste recyclers to create the necessary conditions for the development and growth of the recycled aggregate market;
- Organization 5 is an association reserved for operators in the rubber and elastomer recovery sector, fostering further aggregation potential in the area.

In order to correctly interpret the responses of these substantially different organizations, they have been classified with two logical approaches: a first classification according to the role/mission of the organization, and a second classification according to the position of the organization in the waste-material-product chain.

The first classification divides organizations according to their role in the circular economy, which may be Intermediary, Manufacturer or Association (fig. 1). There is a group of Intermediary organizations who consult and carry out research on sustainability, such as Organization 2 - Intermediary in the en-



1. Classification according to the role of the participant.
All images are reproduced in color in the online edition of the book.



2. Classification according to the position of the participant in the process.

vironmental services sector and Organization 3 - Consulting company for materials and products. Another identified group of organizations are Manufacturers, who create products, like Organization 1 - Producer of indoor rubber floor coverings and Organization 5 - Association of rubber recyclers. The last group comprises Associations that bring organizations together to pursue common values and goals, these include Organization 4 - Association of inert waste recyclers, and Organization 5 - Association of rubber recyclers, hence covering a double role, both manufacturer and association.

The second classification considers the position of the five organizations in the waste-material-product chain, that is the process that transforms waste into new material, then the final product for the market (fig. 2). Participants that are involved in the whole process are Organization 1 - Producer of indoor rubber floor coverings and Organization 2 - Intermediary in the environmental services sector. Two other participants are focused on the initial stage from waste to material: Organization 4 - Association of inert waste recyclers and Organization 5 - Association of rubber recyclers. Involved only in the last stage from material to product, there was Organization 3 - Consulting company for materials and products. It can also be noticed that the organizations positioned between waste and material (4 and 5), coincide with the Associations group in the first classification.

Initially, it was assumed that the roles of stakeholders would be quite specific, namely the interaction between waste managers, producers and designers. During the focus groups and interviews, many other forms were identified, such as manufacturers that in some way cover all three roles in the process (Organization 1), as well as companies that have the Intermediary role (Organization 2 and 3), or even Associations (Organization 4 and 5).

5. Results of the focus groups and interviews

The focus groups and interviews led to identifying problems and needs which could be clustered (fig. 3) in three groups: (1) awareness and communication, (2) quality of information, and (3) product development and evaluation process.

Awareness and communication	Quality of information	Product development and evaluation
channels to reach the market	data verification	definition of material and product characteristics
raising awareness of the circular economy	legislative support	evaluation and visualization of these characteristics
		suggestions on these characteristics
		match between demand and supply

3. Three groups of problems and needs from the focus groups and interviews.

(1) The first group of problems is related to insufficient awareness and communication about circular materials and their value as substitutes for virgin raw materials. In particular, circular materials would need better/additional channels to reach the market (also through advertising), an issue emphasized especially by Organizations 4 and 5 working with waste recyclers. In general, it would be necessary to raise public awareness about the circular economy, as Organization 4 highlighted the problem where recycled materials are often undervalued compared to natural materials. Organization 1 also suggested that dissemination should happen through better storytelling of case studies.

(2) The second group of issues revolves around the quality of sustainability information, related to (lacking) data verification and legislative support. To improve the trustworthiness of declared information on the environmental impact of production materials and processes, different Organizations (2 and 3) emphasized the need to adopt Digital Product Passports. As underlined by Organization 3, verification by an external/legal entity would be helpful because currently, the competition between manufacturers encourages them to codify material information in order to hide their suppliers and keep their advantage. Conversely, furniture companies tend to trust suppliers with material choices. The second problem in this cluster is about legislative support, such as the need to requalify the waste (Organization 2), as well as to move beyond current product end-of-life and control of norms, like Declaration of Performance (Organization 4), or even to create specific by-product legislation (Organization 3).

(3) The third group of problems is focused on the product development and evaluation process, including the definition of material and product characteristics, evaluation and visualization of these suggestions for improvement, and matching between demand and supply. Organization 2 has highlighted the multiplicity of the material and product characteristics, such as cost, performance, quantity, aesthetics, environmental impact, location and logistics, associated sector, processing technology, etc. Another important topic was the evaluation of these char-

acteristics, the relationships between them, such as cost and performance, and their visualization, in particular the intelligibility of data reporting formats (Organization 1 and 2). Finally, Organization 3 raised the need for suggestions according to given or desired material and product characteristics, while Organization 3 emphasized the need for a match between demand and supply.

Based on the focus groups and interview results, it is possible to outline a hypothetical development path. Namely, it envisages a shift from the current linear model to cycles where all stakeholders take responsibility for the proper recycling of waste products. At the same time, in the future product development will need to start with a more advanced, circularity-focused, and data-informed design approach, consciously planning the supply chain from the earliest design phase, in a way that not only minimizes the environmental impact but also allows a cost-effective implementation, which is crucial for maintaining competitivity while moving towards a more sustainable Made in Italy. Moreover, it would be beneficial to implement advanced traceability systems (e.g. Digital Product Passport[3]), continuous legislative support and control, and marketing campaigns to raise awareness.

6. Sustainable future furniture productions

The current research project aims to experiment with new digital tools that may help the transition to a more sustainable and circular Made in Italy production. These digital tools will need to respond to the issues raised by the previously described stakeholders, therefore the focus group findings above will be used as input for deciding the functionalities to experiment with through mockups and functional software prototypes focusing on innovative features, keeping in mind that developing fully featured platforms for all the necessary functionalities is beyond the scope of academic research. Considering the current state of progress, in this section we will discuss a few principles that can be devised already based on the interviews and focus groups, using the previous threefold division: (1) Awareness

and communication; (2) Quality of information; (3) Product development and evaluation.

(1) The first group of issues revolves around the awareness of available circular materials for designers, manufacturers, and consumers themselves, who perceive quality as inferior. While perceptions and generally missing awareness may be addressed with communication actions (out of the research scope), the limited information about available circular materials can be considered an issue to be addressed also with innovative digital tools. Waste exchange platforms are not a new concept, but there is no tool focusing on the needs and territorial peculiarities of Made in Italy furniture. According to the participants, support for various supply chains would be essential, with adequate differentiation of the roles in the platform, providing different levels of authorization and appropriate filterable visualizations.

(2) Another recurring issue is the lack of trustworthy information and the difficulty of finding relevant pieces of information, especially in fields that are not (yet) heavily regulated. While software tools for Digital Product Passports are already well on their way for various product categories due to already passed EU legislation, the conversations have demonstrated a twofold issue: on the one hand, material sourcing information is sensible due to competitive reasons and, on the other hand, there is a general mistrust in how strictly companies follow sustainability standards. While intentionally disregarding rules is a legal matter, better digital tools (e.g. material tracking and reporting) might help avoid unintentional omission of relevant detail, and may proactively invite workers to verify relevant indicators, allowing companies to provide up-to-date information. These tools would need to be user-friendly for various levels of expertise and integrate well with existing methods of tracking, from simple spreadsheets to custom software solutions.

(3) The final group of issues is about the product development and evaluation process. At the moment, designing with circular materials and setting up a trustworthy supply chain is challenging, requiring significant specialized expertise, thus making cir-

cular product development potentially much slower and more expensive. Digital tools may help to bridge this information and expertise gap by providing knowledge and up-to-date supply information at the adequate points of the product design and engineering process. More specifically, considering the expanding range of possibilities offered by artificial intelligence tools, it has been hypothesized that designers, manufacturers and waste managers may benefit from AI tools, but these should be seamlessly integrated in the existing processes and toolchains, possibly acting as software plugins, for example in mainstream CAD and CAM tools. Considering that there is a wide variety of in-house software solutions for managing production and warehouse, a crucial aspect is interoperability: new platforms (or other kinds of solutions) would need to guarantee openness and modularity, either through a proper open source solution, or through publicly available APIs (Application Programming Interfaces) so that any new solution may be quickly integrated into existing tool chains.

7. Conclusions

As described above, the research project has carried out a preliminary analysis of the field, identifying a range of stakeholders within three key categories (waste producers/managers, manufacturers, designers) based on a commonly available classification. Representing the first two categories, a series of interview and focus group sessions have been conducted in order to understand the issues and priorities, revealing three main problematic areas: limited awareness and mistaken perception of circular materials, lack of trust in the quality of environmental impact data about materials, and the difficulty of designing with circular materials and setting up an effective and reliable supply chain. Based on these three areas, possible directions of development have been outlined for the development of experimental digital tools, highlighting the potential of Artificial Intelligence technologies (in particular LLMs) for acting as a well-informed "translator" between various professional figures who otherwise have difficulty with collaborating due to the differences in their professional jargons and mindsets.

In the near future, the work will proceed by defining a set of relevant user journeys from the perspective of the different stakeholders, for whom the research will develop firstly interactive mockups of hypothetical digital tools, then develop software proof-of-concepts to experiment the most promising and innovative functionalities. Hopefully the thus developed knowledge and experiments will contribute to a more effective digital toolbox for the designers and other stakeholders, allowing them to make a leap towards a design approach that prioritizes circular materials and considers environmental impact at all stages from conceptual design to factory setup and disposal.

Notes

[1] Classificazione delle attività economiche ATECO. Istat. (n.d.). https://www.istat.it/classificazione/classificazione-delle-attivita-economiche-ateco/.
[2] Registro Imprese: i dati ufficiali della Camera di Commercio. (n.d.). https://www.registroimprese.it/.
[3] Digital product passports are a system for supply chain traceability. Services like Circularise (https://www.circularise.com/) are leading blockchain platforms that provide digital product passports for end-to-end traceability and secure data exchange for industrial supply chains.

References

Arditi, 2017
Arditi, S. (2017). *Circular economy opportunities in the furniture sector* (p. 55). European Environmental Bureau (EEB). https://eeb.org/wp-content/uploads/2019/05/Report-on-the-Circular-Economy-in-the-Furniture-Sector.pdf

Bakker et al., 2014
Bakker, C., Wang, F., Huisman, J., & den Hollander, M. (2014). Products that go round: Exploring product life extension through design. *Journal of Cleaner Production*, *69*, 10–16. https://doi.org/10.1016/j.jclepro.2014.01.028

Corbin & Strauss, 2008
Corbin, J. M., & Strauss, A. L. (2008). *Basics of qualitative research: Techniques and procedures for developing grounded theory* (3rd ed.). Sage.

EU Commission, 2020
EU Commission. (2020). *Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. A new Circular Economy Action Plan For a cleaner and more competitive Europe*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

Farahmand & Rahimiaghdas, 2024
Farahmand, S. H., & Rahimiaghdas, N. (2024). Circular economy and business transformation in European furniture industry. *Proceedings of The Internation-*

al Conference on Business, Management and Economics, *1*(1), 1–15. https://doi.org/10.33422/icbmeconf.v1i1.207

Kirchherr & Piscicelli, 2019
Kirchherr, J., & Piscicelli, L. (2019). Towards an Education for the Circular Economy (ECE): Five teaching principles and a case study. *Resources, Conservation and Recycling*, *150*, 104406. https://doi.org/10.1016/j.resconrec.2019.104406

Moreno et al., 2016
Moreno, M., De los Rios, C., Rowe, Z., & Charnley, F. (2016). A Conceptual framework for circular design. *Sustainability*, *8*(9), 937. https://doi.org/10.3390/su8090937

Murray et al., 2023
Murray, A. K., Ahlquist, E. T., McKenna, M. K., & Debs, M. (2023). *The Bloomsbury handbook of Montessori education*. Bloomsbury USA Academic.

Nilsson-Lindén, Baumann & Rex, 2019
Nilsson-Lindén, H., Baumann, H., & Rex, E. (2019). LCM development: Focusing on the LC promoters and their organizational problem-solving. *The International Journal of Life Cycle Assessment*, *24*(2), 297–309. https://doi.org/10.1007/s11367-018-1523-z

Pieroni, McAloone & Pigosso, 2019
Pieroni, M. P. P., McAloone, T. C., & Pigosso, D. C. A. (2019). Business model innovation for circular economy and sustainability: A review of approaches. *Journal of Cleaner Production*, *215*, 198–216. https://doi.org/10.1016/j.jclepro.2019.01.036

Potting et al., 2017
Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). *Circular Economy: Measuring innovation in the product chain*. PBL Netherlands Assessment Agency.

Safdar, Yasmin & Anwar, 2021
Safdar, M., Yasmin, M., & Anwar, B. (2021). English for specific purpose through facilitated and nonfacilitated MOOCs: An analysis of the learners' perspectives. *Computer Applications in Engineering Education*, *29*(4), 786–794. https://doi.org/10.1002/cae.22246

Vindrola-Padros & Johnson, 2020
Vindrola-Padros, C., & Johnson, G. A. (2020). Rapid techniques in qualitative research: A Critical review of the literature. *Qualitative Health Research*, *30*(10), 1596–1604. https://doi.org/10.1177/1049732320921835

DIGITAL DESIGN
FOR CIRCULAR MATERIALS

DIGITAL DESIGN FOR CIRCULAR MATERIAL

This line of research is articulated through the projects, Project 1.6 *GLUELESS. Digital Tools for the Design and Evaluation of Glueless Ceramic Solutions* and Project 1.3 *Digitally Enhanced Solutions for the Design Control of Bio-based and Waste-based Materials for the Furniture and Textile Industries*.
"LCA Analysis of Indoor Covering Solutions. Comparison of Ceramic Tiles, Vinyl Tiles, and Laminated Elements with Sustainable Materials" shows how, in Project 1.6, the adoption of thin tiles and environmentally friendly substrates can generate significant environmental benefits, contributing to the sustainability of the ceramic industry.
Project 1.3 is illustrated through its two strands. "Innovative Materials for a More Sustainable textile Industry: Bio-based Polymers and Recycled Fibers – A Short Review" analyzes challenges and prospects of bio-based and biodegradable fibers, presenting already industrialized success stories and emerging technologies (under development) for chemical recycling of fibers.
Instead, "Use of Recycled Ceramic as Cement Substituent for a Circular Made-in-Italy Furniture Industry" explores advantages and critical issues related to the use of waste ceramic powders in low-emission cements, describing some experimental tests. The results open new scenarios for the use of recycled ceramics in the selection of materials for urban furniture.

LCA ANALYSIS OF INDOOR COVERING SOLUTIONS. COMPARISON OF CERAMIC TILES, VINYL TILES, AND LAMINATED ELEMENTS WITH SUSTAINABLE MATERIALS

Stefano Maretti, Alessandro Messori*, Margherita Bandini**, Michele Zannoni***, Veronica Pasini****

1. Introduction

1.1. Ceramic tiles

Ceramic tiles represent one of the most popular indoor and outdoor flooring solutions, with an annual production of 16,7 billion m^2 (2022) (Ceramic Word Review, 2023). The Italian ceramic industry plays a major role globally and registered a production of more than 373 million m^2 in 2023 (Indagini statistiche sull'industria italiana, 2023) even though in decline respect to 2022: 431 million m^2 produced and a total sales volume of 449 million m^2 (Pini et al., 2014). Today, the Italian market remains important, but the industry faces increasing competition from new alternative products. As a result, ceramic companies are increasingly investing in innovation, focusing not only on product quality but also on advanced production processes to maintain their competitiveness internationally.

Since then, the quality of existing products has improved, and some innovations have been proposed to increase the number of fields of applications. Porcelain stoneware tiles are among the most advanced products in the ceramics industry, characterized by their excellent technical and functional proprieties. The term stoneware, in ceramic terminology, denotes a material with a compact body, consisting of various crystalline phases in a glassy matrix. This compactness makes stoneware ceramic a non-porous and resistant material classified according to the international ISO 13006 as BIa. This standard organizes the porosity of ceramic tile materials based on their water absorption value, and BIa is the least porous with a value below 0.5%. Due to its extreme compactness, the porcelain stoneware has a high surface hardness, with values on the Mohs scale between 6 and 8, giving it considerable resistance to abrasion. In addition, it possesses great resistance to mechanical stress, with

**SACMI Imola SC, Imola, Italy*

***Department of Industrial Chemistry "Toso Montanari", Alma Mater Studiorum - University of Bologna, Italy*

****Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

a flexural strength module of more than 50 MPa and remarkable chemical and stain resistances (Romero et al., 2015) high mechanical properties, resistant to chemical substances and cleaning agents, aesthetic possibilities... These characteristics make porcelain stoneware the most suitable to withstand wear and tear of any kind among ceramic flooring materials.

The ceramic life cycle includes various steps: raw material processing; spray-drying; pressing; decoration; firing; cutting; packaging; storage; delivery and disposal.

Starting from the production of ceramic tiles, many natural resources are used, and various environmental impacts can be defined: from raw material extraction to forming and transportation. The most common method of ceramics tiles production includes a wet slurry preparation and a single firing step, in which other relevant water evaporation steps are necessary: spray-drying and oven drying. These two process units contribute relevantly to the total thermal intensity of the process.

This is a high-energy and natural intensive process, with an average water consumption of about 12 liters and an energy expenditure of about 28 kWh per square meter of tile, of which nearly 80% is thermal energy from natural gas (Bresciani et al., 2022).

Despite significant market demand for newly built homes, ceramic tiles are still not the ideal solution for those seeking an economical option for renovation. In fact, the ceramic product is associated not only with its inherent cost but also with high installation costs (which must necessarily be carried out by experienced professionals). In addition, its thickness (normally 10 mm) makes this material unsuitable for the installation on existing flooring, in the absence of structural intervention.

1.2. Luxury Vinyl Tiles – LVT

Among the alternative and commercially available flooring solutions, Luxury Vinyl Tiles or vinyl tiles are attracting increased attention from customers. The LVT tile is present in different solutions on the market, but they all share a layered structure in which the middle layer is made of polyvinyl chloride (PVC), and their final thickness is between 3 and 5 mm.

The middle polymeric or composite material is characterized by the presence of an interlocking mechanism that enables and

simplifies the installation, making them accessible even to less experienced hands (fig. 1).

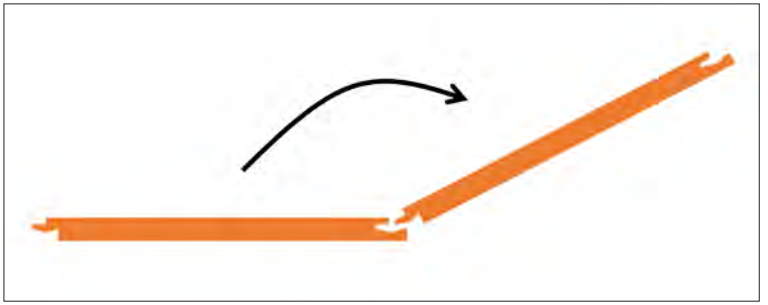
Luxury vinyl tiles are increasing their market share and in 2022 their global value was estimated at $34 billion and is projected to grow up to $76 billion in 2030, with an annual growth rate of 12% (Global Strategic Business Report, 2024).

Part of the success of this product is due to its intrinsic advantages: the quick time between production and use, along with easy transportation due to their low weight make these tiles very attractive for industrial production. In addition, the easy installation and low thickness make LVTs particularly suitable for self-made renovations. However, vinyl flooring solutions come along with non-negligible disadvantages. Firstly, LVT systems display modest durability over time concerning ceramic tiles. In fact, these products are a flooring solution with medium-low wear resistance and low mechanical strength: in the presence of a heavy load on a small surface of the floor (for example, the foot of a piece of furniture) they could be damaged. Moreover, these systems have poor or low water resistance, which can lead to mold formation in damp environments. This makes them unsuitable for certain areas of the house prone to moisture, like bathrooms or basements. Furthermore, they cannot be used outdoors as they tend to deform excessively when exposed to direct sunlight due to heat.

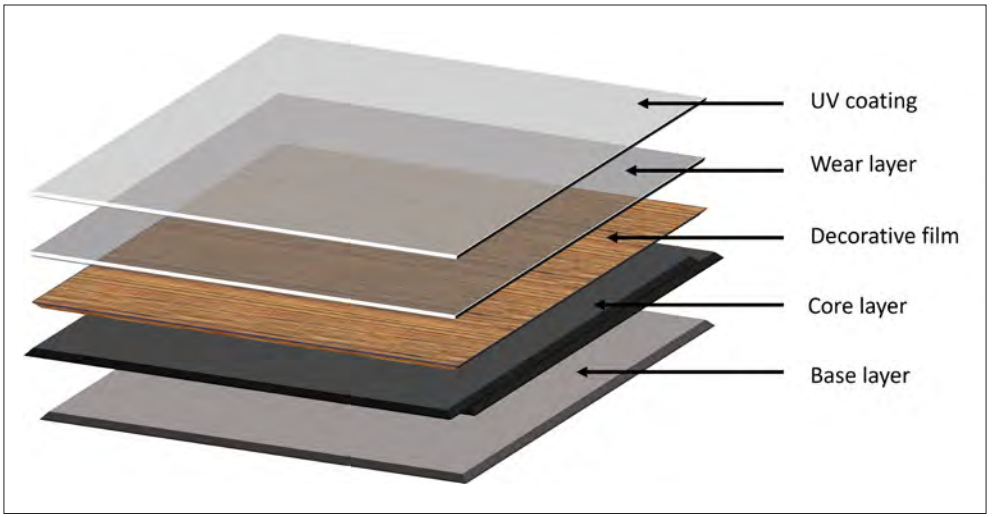
Secondly, another important aspect is the high environmental impact resulting from their production. PVC is produced from vinyl chloride monomer (VCM), obtained from ethylene (from fossil origins) and chlorine and its entire production process consists of several highly impactful and unsustainable steps (Ju, 2016).

No less relevant is the environmental impact of end-of-life LVTs. These are in fact complex polymeric multilayer products, so they are difficult to sort as waste and made mainly of a non-biodegradable polymer (PVC).

Even though vinyl tiles have a relatively long service life (between 10 and 20 years), at the end of their life these materials are accumulated in landfills excluding their waste-to-energy because their incineration causes the production of gases harmful to the environment and humans (Ju, 2016).



1. Example of interlocking mechanism.
All images are reproduced in color in the online edition of the book.



2. Example of the composition of a commercial LVT.





3. Cellulose-based "nonwoven."

1.3. Cellulose airlaid

In recent years, there has been an ongoing effort toward innovative processes and circular products to create more sustainable items. The circular economy has emerged as a major theme in many corporate policies, aiming to minimize raw material needs and consumption, as well as waste production (Giorgi et al., 2017). Among the new sustainable manufacturing processes being explored, the *airlaid* process based on recycled cellulose made from cardboard was evaluated. This method represents a promising innovation in the circular economy, allowing cardboard waste to be transformed into recycled raw materials that can be used in various industries, through a less energy-intensive process and without using process water.

The *airlaid* process involves dispersing the fibers in an air stream and passing them through perforated rotary cylinders or a distribution system to form a sheet on a tape. The *airlaid* process consists of three phases: fiber defibration, web formation, and web blonding. In the defibering stage, the pulp, delivered in highly compressed cardboard-like rolls, is fed into hammer mills rotating at high speed. These separate the pulp into individual dispersed fibers, which are then transported to the web formation system. At the same time, the staple fibers are fed from bales into opening systems that loosen and separate the individual fibers (fig. 3).

At the end of the process, a reel of cellulose-based nonwoven fabric is obtained, and it can be used in a variety of industrial applications like baby diapers, feminine hygiene products, cleaning wipes, and even certain types of insulation and filtration applications (CAMPEN, https://campenmachinery.com/airlaid).

This technology not only promotes sustainability through cardboard recycling but also provides opportunities for the creation of products with reduced environmental impact, contributing to more responsible and circular industrial production (Freville, 2024) regardless of the field of applications (food, electronics, cosmetics, leisure, etc.).

2. Project objectives

The objective of this research is to develop an alternative and innovative solution to Luxury Vinyl Tiles (LVT) and traditional ceramics tiles, currently available on the market. It aims to create a coupled system consisting of a substrate support and thin porcelain stoneware tile that outstands the wear and tear properties of LVT.

The project focuses on environmental sustainability, aiming to the promotion and use of reclaimed and recycled materials in the composition of layered products. This approach targets not only the reduction of natural resource consumption but also the energy consumption and logistical costs associated with the production and transportation of materials.

To test the validity of our sustainability goals, we conducted a Life Cycle Analysis (LCA) of a series of benchmark multilayer systems, comparing them with traditional tiles and LVT. By means of this analysis, the research aims to contribute to the production of eco-friendly flooring proceeding by an LCA-driven innovation, improving energy efficiency and reducing the overall impact related to classical flooring products. The overall environmental impact of the different solutions was evaluated, and the most sustainable ones were identified.

3. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) represents an analytical and systematic methodology used to assess the environmental impact of a product or service throughout its life cycle. This assessment covers all stages, from raw material extraction to production to the final disposal, allowing for quantification of the environmental impacts associated with each life cycle stage (European Commission. Joint Research Centre. Institute for Environment and Sustainability, 2010).

In the present study, a detailed LCA analysis was commissioned to EcamRicert Srl. The goal is to examine the results of this analysis and derive the necessary information for the development of new sustainable product concepts.

The LCA analysis divides the environmental footprint into

several impact categories, which represent various effects on the environment. This approach provides a fundamental technical basis for implementing sustainability strategies within production chains, enabling an in-depth understanding of the environmental impacts generated by products, services, and economic systems. Defining the system boundaries (i.e., the scope of analysis) in an LCA study is crucial for managing and mitigating calculated impacts, identifying opportunities for improvement that promote informed decisions and increased overall sustainability (Klöpffer & Grahl, 2014).

Life cycle analysis consists of four main steps:

1. Definition of aim and objectives of the analysis: (Goal and scope definition).
2. Inventory of input (resource consumption) and output (releases to the environment) (Life Cycle Inventory LCI).
3. Assessments of the environmental impacts that are generated from releases to the environment and resource consumption (Life Cycle Impact Assessment LCIA).
4. Evaluation of the results and indication of improvements (Life Cycle Interpretation LCI).

3.1. System boundaries

System boundaries circumscribe a spatial, temporal, and operation area within which to collect reliable data that reflect the actual environmental performance of the system and give a complete description of it. The detail and extent of the study are defined by these boundaries, which allow the determination of unit processes to be included in the model. Along with these unit processes, macro-consumptions involved were identified and the calculation model was set up and analyzed. The information and data collected are considered representative of both the actual situation with reference to the product system studied and the geographical area where these processes are carried out. A complete cradle-to-grave system assessment is also carried out, in which all stages of the product life cycle are evaluated to identify the system stages that have the greatest environmental impact (fig. 4). The system boundaries studied include the following life cycle stages:

- A1. Raw material supply;
- A2. Transport;
- A3. Manufacturing;
- A4. Transport to the site;
- A5. Assembly;
- C4. Disposal;

Primary data were given by the company Sacmi Imola, and they constituted the primary source of information for the inventory analysis. The latter can be grouped according to environmental performance indicators, to which the results of environmental performance will subsequently be referred. The identifiable environmental performance indicators are shown in table 1.

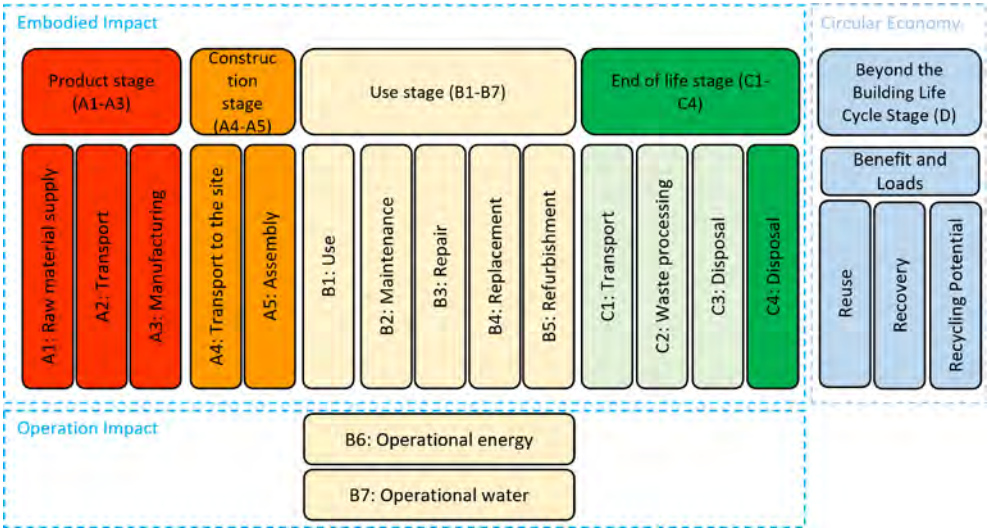
Tab. 1. Environmental performance indicators investigated for component modules in the production phase.

Modules	Indicator	
A1	Raw material	CRADLE TO GATE
	Electricity consumption	
	Thermal energy consumption	
A2	Transportation	
A3	Water consumption	
	Waste and emissions	
	Packaging	
A4	Transportation	OPTION
A5	Interfloor*	
C4	Waste	

*mortar or mat

The objective of this phase is to model the results of the inventory analysis in environmental performance data (i.e., the "eco-profile") in order to produce reliable and easy-to-understand results as well as to evaluate the magnitude of these results along the investigated modules.

The geographic boundaries of module A3 are the Italian national territory while A1 and A2, are considered national and international territories.



4. Phases included in the system boundaries.

3.2. Life Cycle Inventory (LCI) and Data Modeling Parameters

The inventory analysis addresses the definition, qualification, and compilation of material and energy flows involved in the production of households studied. This phase is conducted according to the guidance provided by UNI EN ISO 14044:2021, which defines the processing unit as the "smallest element considered in the life cycle inventory analysis for which input and output data are quantified." Data on environmental aspects (Life Cycle Inventory) must ensure accurate and truthful analysis of environmental impact (Giorgi et al., 2017). Life cycle data on materials or energy input are classified into three main categories: specific data, selected generic data, and unselected generic data. Specific data are collected directly at the production plant where product-specific processes are carried out. These also include data from other parts of the life cycle, reconnected to the specific system under study. Instead, selected generic data come from commonly available sources and are used when specific data are not available or when it is necessary to complete missing information in the Life Cycle Inventory.

3.3. Life Cycle Impact Assessment (LCIA)

The categories that are shown in table 2 were selected for the Life Cycle Impact Assessment (LCIA).

Tab. 2. List of impact categories used in accordance with the reference PCR.

Category	**Acronym**	**U.M.**
Climate change	GWP-Total	kg CO_2 eq
Ozone depletion	PODP	kg CFC11 eq
Acidification	AP	mol H+ eq
Eutrophication, freshwater	EP-freshwater	kg P eq
Eutrophication, marine	EP-marine	kg N eq
Eutrophication, terrestrial	EP- terrestrial	mol N eq
Photochemical ozone formation	POCP	kg NMVOC eq
Resource use, minerals, and metals	ADP-minerals and metals	kg Sb eq
Resource use, fossil	ADP-fossil	MJ

SimaPro calculation software (Simapro 91_-1 v 9.0.0.49 Developer) was used for inventory processing and calculation of eco-profiles. ECOINVENT databases were selected, while for the characterization of inventory data with reference to the various types of impacts on which the system under consideration acts, EN 15804 was applied as the calculation method.

The performance categories recalled in table 2 are briefly described:

- Climate change / Global warming. Includes greenhouse gas emissions and is measured by its CO_2 equivalent (Solomon et al., 2007);
- Ozone layer depletion. Category that refers to stratospheric ozone depletion on a global scale. The unit of measurement is trichlorofluoromethane equivalent;
- Acidification. Acidification can be caused by emissions to the atmosphere, water, and soil from combustion processes (electricity, heating) and transportation. The unit of measurement is moles H+ equivalent;
- Eutrophication (freshwater, marine, terrestrial). Eutrophication impacts ecosystems due to substances containing nitrogen (N) or phosphorus (P) that cause specific algae or plant growth and limit oxygen availability. The units of measurement are kilograms of phosphorus (P) equivalent (Eutrophication, freshwater); kilograms of nitrogen (N) equivalent (Eutrophication, marine); and moles of nitrogen (N) equivalent (Eutrophication, terrestrial);
- Photochemical oxidation. Ozone in the troposphere, caused mainly by photochemical smog, is harmful to living organisms and can increase the frequency of respiratory problems. The unit of measurement is kg of non-methane volatile organic compounds (NMVOC) equivalent;
- Abiotic depletion (Resource use, minerals and metals, Resource use, fossil). This parameter indicates the depletion of mineral resources as a result of raw material extraction and is measured in kg of antimony (Sb) equivalent (Resource use, minerals, and metals) and MJ (Resource use, fossil);
- Water Use. Assesses the potential deprivation of water, for humans or ecosystems, based on the assumption that the

less water remains available per area, the more likely it is that another user will be deprived. The unit of measurement is the m^3 of deprived water equivalent.

3.4. Goal and scope definition

The study conducted a life cycle analysis (LCA) of 12 different scenarios by comparing 1 m^2 of flooring surface (tab. 3). Each scenario is listed here with its relative specific weight relative to 1 m^2 of covered area.

Tab. 3. Scenarios examined.

Scenario	Materials	kg/m²
Scenario 1	5 mm LVT	8,9
Scenario 2	6 mm ceramic	13,8
Scenario 3	2 mm ceramic + glue* + 4 mm LVT	12,1
Scenario 4	2 mm ceramic + 4 mm LVT	11,8
Scenario 5	3 mm ceramic + glue* + 4 mm LVT	14,5
Scenario 6	3 mm ceramic + 4 mm LVT	14,2
Scenario 7	3 mm ceramic + glue* + 3 mm compacted airlaid	10,1
Scenario 8	ceramic 3 mm + glue* + airlaid compacted 3 mm 100% recycled	10,1
Scenario 9	2 mm ceramic + glue* + 3 mm compacted airlaid 100% recycled	8,9
Scenario 10	ceramic 2 mm + low-impact glue + airlaid compacted 3 mm 100% recycled	8,9
Scenario 11	2 mm ceramic + low-impact glue + 3 mm compacted airlaid 100% recycled + 100% renewable energy	8,9
Scenario 12	8 mm ceramic	18,4

* two-component polyurethane glue

3.5. Functional unit

The unit in which all the scenarios are compared is 1 m^2 of pavement area for each case study. This reference is crucial for combining the flows attributed to the object of analysis and for assessing the environmental impacts related to the specific individual phases of the product life cycle. The choice of the stated unit is in accordance with the reference standards and essential for the calculation of the eco-profile.

4. Interpretation of results

The results of the Life Cycle Assessment (LCA) presented in table 4 illustrate the overall contribution of various impact categories for each scenario analyzed. The data are expressed in specific impacts for each predefined category, using appropriate units of measurement. The total impact for each category is calculated by aggregating the contributions from all inputs and outputs included in the inventory.

From table 4, it emerges that the most significant impact categories are climate change, fossil resource use, and water use. More in detail we focused our attention on a series of benchmark scenarios in order to represent a range of situations. Doing so the variables and dynamics that influence the overall environmental impacts and direct us to the project objective can be better rationalized and compared. In particular, scenario 1 represents the "classical" LVT solution, while scenario 2 is the corresponding "classical" ceramic tile product. On the other hand, scenario 5 is the combination of the two approaches: a thin ceramic tile (3 mm) and a 4 mm LVT substrate, joined by glue. This layered product is compared with scenario 10, where a slimmer ceramic tile (2 mm) is applied to a recycled cellulose airlaid substrate. Finally, scenario 11 comprises the layered solution of scenario 10 while adding the use of renewable energy and low-impact glue.

From these benchmark scenarios, we can draw some comments. In particular, scenario 1, shows the highest value in the water use category, with 58 m^3 of water deprivation, indicating a significant potential impact on water availability for humans and ecosystems. This scenario is also characterized by considerable greenhouse gas emissions, mainly due to PVC production, and a high fossil resource use associated with the intensive use of non-renewable raw materials for the production of LVT and two-component PU adhesive.

By comparison, scenario 2 presents the lowest values in the Resource use fossil and Water use categories, with 108 MJ and 1.97 m^3 of water deprivation, respectively (tab. 4). On the other hand, scenario 5, shows the maximum impact on climate change, largely due to emissions from PVC production further amplified by the use of fossil fuels. Again, a high consumption

Tab. 4. Environmental performance relative to all scenarios examined.

Impact categories	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Climate change	kg CO_2 eq	2,10E+01	1,03E+01	2,32E+01	2,15E+01
Ozone depletion	kg CFC11 eq	5,45E-06	1,09E-06	5,19E-06	4,97E-06
Acidification	mol H+ eq	1,01E-01	6,47E-02	1,32E-01	1,23E-01
Eutrophication, freshwater	kg P eq	5,76E-03	8,59E-04	5,58E-03	5,13E-03
Eutrophication, marine	kg N eq	1,88E-02	1,41E-02	2,58E-02	2,31E-02
Eutrophication, terrestrial	mol N eq	1,80E-01	1,52E-01	2,50E-01	2,31E-01
Photochemical	kg NMVOC eq	6,48E-02	3,84E-02	7,98E-02	7,46E-02
Resource use, minerals and metals	kg Sb eq	1,22E-03	3,28E-05	1,06E-03	1,03E-03
Resource use, fossils	MJ	4,20E+02	1,08E+02	4,23E+02	3,94E+02
Water use	m3 depriv.	5,80E+01	1,97E+00	5,71E+01	5,57E+01

of "Resource of fossil" (108 MJ) is observed. Scenario 10, despite using recycled materials, presents a Water use of 42.2 m^3, highlighting the need for further improvements in the production cycle (tab. 4). In this scenario, "Resource fossil use" consumption is 166 MJ, not among the most impactful but still significant, and with a climate change contribution of 11.6 kg CO_2 eq. Finally, scenario 11, shows a significant reduction in greenhouse gas emissions, with a value of 7.86 kg CO_2 eq, thus mitigating the impact in the climate change category. It also shows lower consumption of both "Resource use fossil" (129 MJ) and "Water use" (40.6 m^3) compared to scenario 10.

In summary, the most critical impact categories are climate change and fossil resource use, which vary significantly across the scenarios. Water use also represents a considerable impact category for all the scenarios examined.

4.1. Scenario analysis

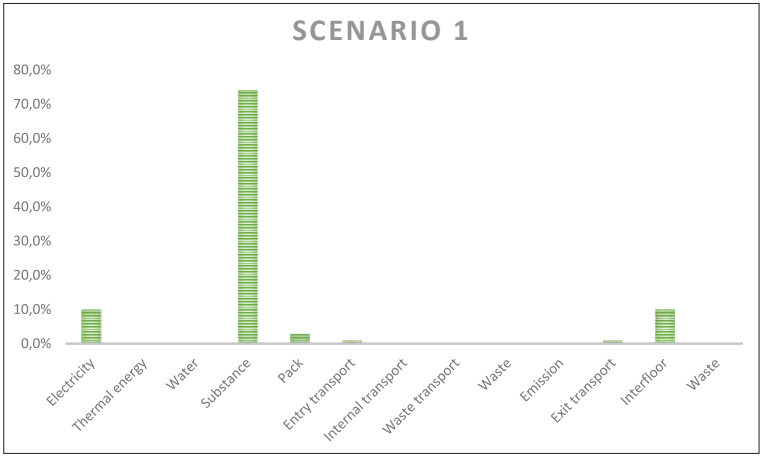
To further explore the analysis, we continued analyzing benchmark scenarios 1, 2, 5, 10, and 11. (The complete list of tables and impacts of the 12 scenarios are reported in the Appendix).

Below we reported the average percentage distributions of the impact regarding the investigated environmental performance indicators of the various scenarios. This type of graph is indicative of how much each indicator weighs on the total impact, highlighting those of greatest concern.

Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12
2,39E+01	2,29E+01	1,39E+01	1,34E+01	1,32E+01	1,16E+01	7,86E+00	1,38E+01
5,61E-06	5,14E-06	1,95E-06	1,95E-06	1,92E-06	1,72E-06	1,36E-06	1,45E-06
1,39E-01	1,29E-01	8,51E-02	8,29E-02	8,15E-02	7,23E-02	5,81E-02	8,63E-02
5,71E-03	5,26E-03	1,74E-03	1,65E-03	1,58E-03	1,14E-03	3,63E-04	1,14E-03
2,73E-02	2,47E-02	1,67E-02	1,64E-02	1,60E-02	1,35E-02	1,06E-02	1,87E-02
2,67E-01	2,49E-01	1,67E-01	1,63E-01	1,60E-01	1,42E-01	1,13E-01	2,03E-01
8,40E-02	7,90E-02	4,68E-02	4,57E-02	4,48E-02	3,99E-02	3,26E-02	5,13E-02
1,06E-03	1,03E-03	2,61E-04	2,59E-04	2,58E-04	2,29E-04	1,95E-04	4,37E-05
4,48E+02	4,09E+02	2,15E+02	1,96E+02	1,93E+02	1,66E+02	1,29E+02	1,43E+02
5,74E+01	5,60E+01	4,40E+01	4,37E+01	4,36E+01	4,22E+01	4,06E+01	2,63E+00

Scenario 1: 5 mm LVT

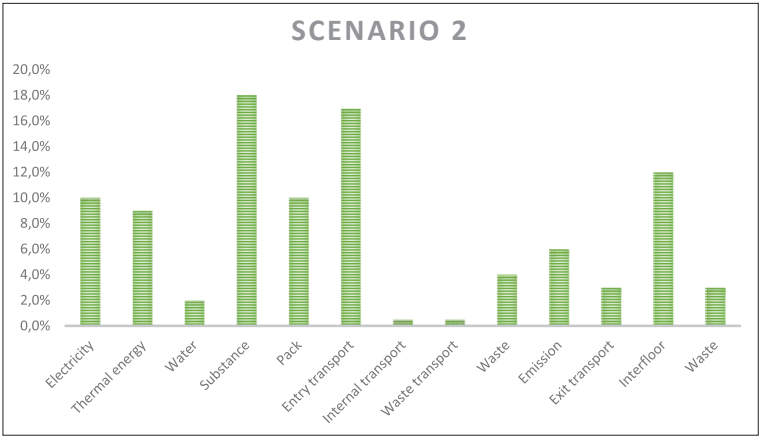
In scenario 1, which involves the use of 5 mm Luxury Vinyl Tile (LVT), a significant impact is observed in the material category, with about 75% of the total impact attributable to the composition of LVT (fig. 5). PVC polymer, being of fossil origin and not recyclable appears to be the largest contributor to the poor sustainability of the LVT product.



5. Average percentage distribution of the impact of the investigated environmental performance indicators, relative to scenario 1.

Scenario 2: 6 mm ceramic

Scenario 2, which consists entirely of 6mm ceramic tiles, shows that even in this case the main impact is observed in the material category, accounting for 18% of the total impact (fig. 6). In addition, compared to scenario 1, the parameters related to electricity, thermal energy, and water consumption also appear to make a significant contribution. In fact, one of the main problems associated with the production of ceramic tiles is their forming and firing process, which is extremely energy-intensive. In addition, another major factor is the incoming transportation, which contributes 17% of the total impact. This impact is due to the import of ceramic raw materials from different parts of the world, requiring both sea and road transportation. Finally, the interfloor material (mortar) is also a non-negligible component by contributing to 12% of the total impact.



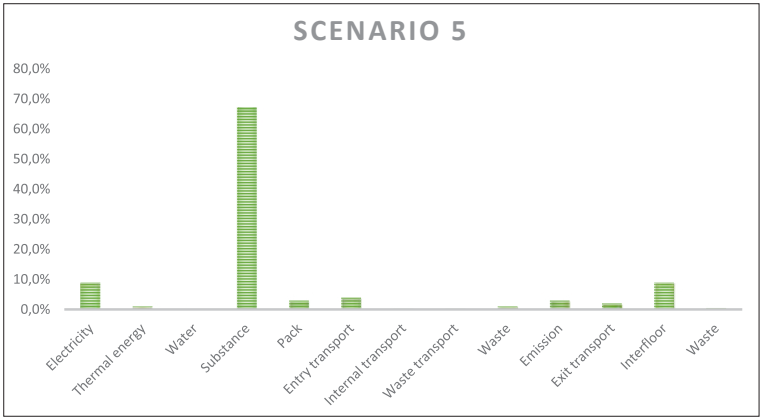
6. Average percentage distribution of the impact of the investigated environmental performance indicators, relative to scenario 2.

Scenario 5: 3mm ceramic, glue, and 4 mm LVT

Scenario 5 is distinguished by the use of 3 mm ceramic combined with glue and 4 mm LVT. This scenario is found to have the greatest environmental impact of all those analyzed. Although 3-mm ceramics require less energy for firing than thicker ones, in the presence of LVT the total material contribution becomes extremely impactful (fig. 7). In addition, this laminate has a two-component glue and interfloor backing mat inside it, which in turn affects the sustainability of the product. However, at a reduced ceramic thickness, the energy impact is lower than

in scenario 2 due to the minor quantity of material to be fired per square meter.

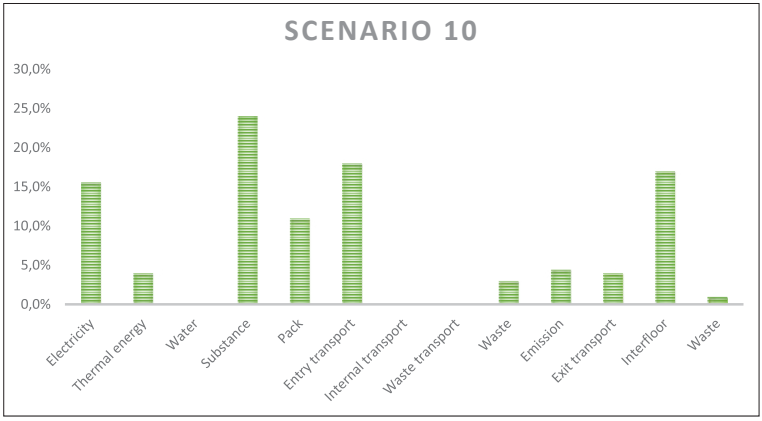
7. Average percentage distribution of the impact of the investigated environmental performance indicators, relative to scenario 5.



Scenario 10: 2 mm ceramic, low impact glue, and 3 mm cellulose airlaid

Scenario 10 involves the use of 2 mm ceramic laminated with 3 mm cellulose airlaid and low-impact glue. This combination was chosen to reduce energy impact by lowering the impact associated with the substrate material and increasing the use of recycled products. The use of cellulose airlaid, derived from recycled cardboard, significantly reduces the environmental impact. Compared with scenario 5, 10 reports a less influential substance category by 34 percent points (fig. 8). However, the overall impact remains slightly higher than for ceramics alone.

8. Average percentage distribution of the impact of the investigated environmental performance indicators, relative to scenario 10.



Regarding the impacts of thermal energy and electricity, scenario 10 has a slightly higher impact than that of ceramics alone (scenario 2), although the addition of a recycled material. This significant contribution, especially of electrical energy, is probably due to the airlaid manufacturing process.

Scenario 11: 2 mm ceramic, low impact glue, 3 mm cellulose airlaid with renewable energy

The least impactful scenario consists of 2 mm ceramic, low-impact glue, and 3 mm cellulose airlaid and uses renewable energy. In fact, if 100% renewable energy is added to the production, furthermore the addition of low-impact glue for the joining of its mating materials results in a lower overall average percentage contribution than all scenarios examined. The combination of low-impact materials and renewable energy contributes to a significantly more sustainable energy profile than the other scenarios.

Impact of interfloor

A relevant impact category for all scenarios is the interfloor. This material represents the interface between the floor and the bottom, which in ceramic-only cases, is the mortar, while in other scenarios a polymer mat is used. The significant average impact of this component varies between 10-20%. This non-negligible figure thus introduces further impetus for redesign and innovation in laying processes in search of more sustainable solutions. The next goal will be to reduce the environmental impact of this category by developing interlocking laying methods that require neither mortar nor mat.

5. Conclusion

The analysis conducted on all the studied scenarios shows that module A1, comprising thermal energy, electricity, and matter, are the most impactful categories and among them the most concerning is matter. Scenario 5 appears to be the most impactful in terms of climate change and fossil resource use, confirming that lowering the ceramic tile thickness and associating it with LVT is not a feasible strategy. The LVT tile alone is absolutely unsus-

tainable compared to other layered solutions involving ceramic, mostly in terms of water use. In contrast, the 6 mm ceramic scenario 2 emerges as the least impactful of all three, showing a significantly more sustainable environmental profile. In this comparison it appears significant how ceramic products, even if highly energetically demanding, are a more sustainable alternative to LVT. To further reduce their impact, one of the feasible strategies might be the reduction of their thickness as in scenarios 10 and 11. However, the backing of the thin 2 mm tile with recycled material as the cellulose airlaid might be a suitable solution only if the energy comes from renewable sources. In fact, scenario 10 is less impactful than scenario 5 due to the use of low-impact glue and airlaid backing, even though sustainability is reached only when the integration of thin ceramics, recycled materials, and sustainable energy are all implemented (scenario 11). Lastly, the interfloor (a polymeric mat or mortar) represents a significant factor in the overall impact of these products.

Thanks to this LCA analysis it is possible to draw the boundaries of our project. The attention will be drawn to the production of thin ceramic materials coupled with recycled materials, using no glue or low-impact glue. Another important aspect is the optimization of the laying procedures, to minimize the interfloor impact and create a facile system for the customer.

References

Bresciani & Ricci, 2022
Bresciani, A., & Ricci, C. (2022). *New developments for ceramic plants with low environmental impact*. Qualicer.

Camera dei deputati, n.d.
Camera dei deputati. (n.d.). *Il Piano Nazionale di Ripresa e Resilienza*. Documentazione parlamentare. Retrieved August 29, 2024, from https://temi.camera.it/leg19/pnrr.html

CAMPEN, n.d.
CAMPEN. (n.d.). Airlaid–Machines & technology for airlaid production. *CAMPEN*. Retrieved July 26, 2024, from https://campenmachinery.com/airlaid

Ceramic World Review, 2023
Ceramic World Review. (2023). *153*. https://ceramicworldweb.com/en/magazines/ceramic-world-review-1532023

European Commission, 2010
European Commission. Joint Research Centre. Institute for Environment and Sustainability. (2010). *International Reference Life Cycle Data System (ILCD)*

Handbook : general guide for life cycle assessment: Detailed guidance. Publications Office. https://data.europa.eu/doi/10.2788/38479

Freville, 2024
Freville, E. (2024). Novel technologies for producing tridimensional cellulosic materials for packaging: A review. *Carbohydrate Polymers*, *342*. https://doi.org/10.1016/j.carbpol.2024.122413

Giorgi, Lavagna & Campioli, 2017
Giorgi, S., Lavagna, M., & Campioli, A. (2017). Economia circolare, gestione dei rifiuti e life cycle thinking: fondamenti, interpretazioni e analisi dello stato dell'arte. *Ingegneria dell'Ambiente*, *4*(3). https://doi.org/10.14672/ida.v4i3.1141

Giorgi et al., 2017
Giorgi, S., Lavagna, M., Campioli, A., & di Milano, P. (2017). Procedure di allocazione nella metodologia LCA e tendenze settoriali verso un'economia circolare. *XI Convegno della Rete Italiana LCA Resource Efficiency e Sustainable Development Goals: il ruolo del Life Cycle Thinking*. https://www.researchgate.net/publication/333377827

Global Strategic Business Report, 2024
Global Strategic Business Report. (2024). https://www.researchandmarkets.com/reports/5302603/luxury-vinyl-tiles-lvt-flooring-global

Indagini statistiche sull'industria italiana, 2023
Indagini statistiche sull'industria italiana. (2023). Confindustria Ceramica. https://confindustriaceramica.it/w/indagine-statistica-nazionale

ISO, 2004
ISO. (2004). *Environmental management systems – Requirements with guidance for use, International Standards Organisation*.

ISO, 2010
ISO. (2010). *Environmental labels and declarations. Type III environmental declarations. Principles and procedures, International Standards Organisation*.

ISO (UNI EN ISO 14040)
ISO (UNI EN ISO 14040). *Environmental management, Life Cycle Assessment – Principles and Framework*. Geneva: International Organization for Standardization (ISO).

ISO (UNI EN ISO 14044)
ISO (UNI EN ISO 14044). *Environmental management, Life Cycle Assessment – Requirements and Guidelines*. Geneva: International Organization for Standardization (ISO).

Ju, 2016
Ju, J. (2016). Thermal degradation of PVC: A review. *Waste Management*, *48*, 300–314. https://doi.org/10.1016/j.wasman.2015.11.041

Klöpffer & Grahl 2014
Klöpffer, W., & Grahl, B. (2014). *Life Cycle Assessment (LCA): A guide to best practice*. Wiley-VCH.

Pini et al., 2014
Pini, M., Ferrari, A. M., Gamberini, R., Neri, P., & Rimini, B. (2014). Life cycle

assessment of a large, thin ceramic tile with advantageous technological properties. *The International Journal of Life Cycle Assessment*, *19*(9), 1567–1580. https://doi.org/10.1007/s11367-014-0764-8

Romero & Pérez, 2015
Romero, M., & Pérez, J. M. (2015). Relation between the microstructure and technological properties of porcelain stoneware. A review. *Materiales de Construcción*, *65*(320), e065. https://doi.org/10.3989/mc.2015.05915

SACMI, 2024
SACMI. (2024, August 5). https://www.sacmi.it/it-IT/

Solomon et al., 2007
Solomon, S., IPCC, et al. (2007). *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC*. Cambridge University Press.

Appendix

Scenario 1

Impact categories	Unit	Electricy	Heat energy	Water	Substance	Pack	Entrance transportation
Climate change	kg CO_2 eq	3,86E+00	0,00E+00	3,32E-03	1,34E+01	4,34E-01	4,62E-01
Ozone depletion	kg CFC11 eq	3,80E+00	0,00E+00	3,30E-03	1,30E+01	4,20E-01	4,61E-01
Acidification	mol H+ eq	5,91E-02	0,00E+00	1,42E-05	-3,32E-01	1,28E-02	1,92E-04
Eutrophication, freshwater	kg P eq	6,75E-04	0,00E+00	5,72E-06	7,19E-01	1,57E-03	1,73E-04
Eutrophication, marine	kg N eq	5,20E-07	0,00E+00	2,21E-10	4,11E-06	4,13E-08	1,15E-07
Eutrophication, terrestrial	mol N eq	1,86E-02	0,00E+00	1,84E-05	6,10E-02	2,23E-03	1,47E-03
Photochemical	kg NMVOC eq	9,77E-04	0,00E+00	2,38E-06	4,53E-03	1,17E-04	3,00E-05
Resource use, minerals and metals	kg Sb eq	2,75E-03	0,00E+00	3,55E-06	1,31E-02	7,69E-04	3,29E-04
Resource use, fossils	MJ	3,06E-02	0,00E+00	3,36E-05	1,21E-01	6,82E-03	3,59E-03
Water use	m3 depriv.	7,67E-03	0,00E+00	9,03E-06	4,59E-02	1,59E-03	9,17E-04

Scenario 2

Impact categories	Unit	Electricy	Heat energy	Water	Substance	Pack	Entrance transportation
Climate change	kg CO_2 eq	8,83E-01	2,34E+00	2,39E-03	1,13E+00	4,34E-01	1,77E+00
Ozone depletion	kg CFC11 eq	8,69E-01	2,34E+00	2,37E-03	1,10E+00	4,20E-01	1,77E+00
Acidification	mol H+ eq	1,35E-02	4,67E-04	1,02E-05	2,28E-03	1,28E-02	6,39E-04
Eutrophication, freshwater	kg P eq	1,54E-04	1,54E-04	4,12E-06	2,50E-02	1,57E-03	8,76E-04
Eutrophication, marine	kg N eq	1,19E-07	2,96E-07	1,59E-10	1,45E-07	4,13E-08	4,10E-07
Eutrophication, terrestrial	mol N eq	4,26E-03	3,16E-03	1,32E-05	6,52E-03	2,23E-03	2,33E-02
Photochemical	kg NMVOC eq	2,24E-04	2,97E-05	1,71E-06	3,50E-04	1,17E-04	9,53E-05
Resource use, minerals and metals	kg Sb eq	6,30E-04	7,73E-04	2,55E-06	1,59E-03	7,69E-04	5,64E-03
Resource use, fossils	MJ	7,02E-03	8,36E-03	2,42E-05	1,65E-02	6,82E-03	6,26E-02
Water use	m3 depriv.	1,76E-03	2,33E-03	6,50E-06	4,10E-03	1,59E-03	1,53E-02

Inland transport	Waste transportation	Waste	Emission	Outland transportation	Interfloor	Waste	Total
0,00E+00	0,00E+00	0,00E+00	0,00E+00	4,26E-01	2,35E+00	0,00E+00	2,10E+01
0,00E+00	0,00E+00	0,00E+00	0,00E+00	4,26E-01	2,35E+00	0,00E+00	2,05E+01
0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,77E-04	-8,33E-03	0,00E+00	-2,68E-01
0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,60E-04	7,14E-04	0,00E+00	7,23E-01
0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,06E-07	5,51E-07	0,00E+00	5,45E-06
0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,36E-03	1,63E-02	0,00E+00	1,01E-01
0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,77E-05	7,68E-05	0,00E+00	5,76E-03
0,00E+00	0,00E+00	0,00E+00	0,00E+00	3,04E-04	1,54E-03	0,00E+00	1,88E-02
0,00E+00	0,00E+00	0,00E+00	0,00E+00	3,32E-03	1,47E-02	0,00E+00	1,80E-01
0,00E+00	0,00E+00	0,00E+00	0,00E+00	8,46E-04	7,92E-03	0,00E+00	6,48E-02

Inland transport	Waste transportation	Waste	Emission	Outland transportation	Interfloor	Waste	Total
3,32E-03	1,44E-03	1,27E-03	2,75E+00	7,15E-02	8,95E-01	7,35E-02	1,03E+01
3,31E-03	1,43E-03	1,27E-03	2,75E+00	7,14E-02	9,73E-01	7,34E-02	1,04E+01
2,72E-06	5,96E-07	1,43E-06	0,00E+00	1,84E-05	-7,90E-02	8,24E-05	-4,92E-02
1,33E-06	5,38E-07	2,86E-07	0,00E+00	5,21E-05	2,80E-04	1,65E-05	2,81E-02
5,43E-09	3,58E-10	6,30E-10	0,00E+00	1,42E-08	1,82E-08	3,63E-08	1,09E-06
3,96E-05	4,57E-06	9,94E-03	9,93E-03	2,32E-03	2,30E-03	7,20E-04	6,47E-02
2,48E-07	9,32E-08	7,26E-08	0,00E+00	2,34E-06	3,43E-05	4,18E-06	8,59E-04
5,08E-06	1,02E-06	1,79E-03	1,79E-03	5,71E-04	2,14E-04	2,72E-04	1,41E-02
5,57E-05	1,12E-05	1,97E-02	1,96E-02	6,35E-03	2,18E-03	2,99E-03	1,52E-01
1,52E-05	2,85E-06	5,02E-03	5,01E-03	1,55E-03	1,00E-03	7,26E-04	3,84E-02

Scenario 5

Impact categories	Unit	Electricy	Heat energy	Water	Substance	Pack	Entrance transportation
Climate change	kg CO_2 eq	4,30E+00	4,57E-01	4,51E-03	1,32E+01	4,34E-01	1,04E+00
Ozone depletion	kg CFC11 eq	5,80E-07	4,03E-07	3,00E-10	3,60E-06	4,13E-08	2,42E-07
Acidification	mol H+ eq	2,08E-02	1,63E-03	2,50E-05	6,26E-02	2,23E-03	1,32E-02
Eutrophication, freshwater	kg P eq	1,09E-03	1,32E-05	3,24E-06	4,30E-03	1,17E-04	5,68E-05
Eutrophication, marine	kg N eq	3,07E-03	3,05E-04	4,82E-06	1,42E-02	7,69E-04	3,19E-03
Eutrophication, terrestrial	mol N eq	3,42E-02	3,32E-03	4,58E-05	1,26E-01	6,82E-03	3,54E-02
Photochemical	kg NMVOC eq	8,55E-03	9,63E-04	1,23E-05	4,45E-02	1,59E-03	8,68E-03
Resource use, minerals and metals	kg Sb eq	4,16E-05	1,87E-07	2,22E-08	8,28E-04	2,02E-06	2,15E-06
Resource use, fossils	MJ	5,45E+01	2,89E+01	4,98E-02	2,66E+02	5,83E+00	1,55E+01
Water use	m3 depriv.	2,88E+00	9,87E-03	5,86E-01	1,36E+01	-1,06E-02	4,68E-02

Scenario 10

Impact categories	Unit	Electricy	Heat energy	Water	Substance	Pack	Entrance transportation
Climate change	kg CO_2 eq	8,83E-01	2,34E+00	2,39E-03	1,13E+00	4,34E-01	1,77E+00
Ozone depletion	kg CFC11 eq	8,69E-01	2,34E+00	2,37E-03	1,10E+00	4,20E-01	1,77E+00
Acidification	mol H+ eq	1,35E-02	4,67E-04	1,02E-05	2,28E-03	1,28E-02	6,39E-04
Eutrophication, freshwater	kg P eq	1,54E-04	1,54E-04	4,12E-06	2,50E-02	1,57E-03	8,76E-04
Eutrophication, marine	kg N eq	1,19E-07	2,96E-07	1,59E-10	1,45E-07	4,13E-08	4,10E-07
Eutrophication, terrestrial	mol N eq	4,26E-03	3,16E-03	1,32E-05	6,52E-03	2,23E-03	2,33E-02
Photochemical	kg NMVOC eq	2,24E-04	2,97E-05	1,71E-06	3,50E-04	1,17E-04	9,53E-05
Resource use, minerals and metals	kg Sb eq	6,30E-04	7,73E-04	2,55E-06	1,59E-03	7,69E-04	5,64E-03
Resource use, fossils	MJ	7,02E-03	8,36E-03	2,42E-05	1,65E-02	6,82E-03	6,26E-02
Water use	m3 depriv.	1,76E-03	2,33E-03	6,50E-06	4,10E-03	1,59E-03	1,53E-02

Inland transport	Waste transportation	Waste	Emission	Outland transportation	Interfloor	Waste	Total
3,32E-03	7,18E-04	6,37E-04	1,38E+00	6,94E-01	2,35E+00	3,00E-02	2,39E+01
5,43E-09	1,79E-10	3,15E-10	0,00E+00	1,73E-07	5,51E-07	1,48E-08	5,61E-06
3,96E-05	2,29E-06	9,94E-03	9,93E-03	2,21E-03	1,63E-02	2,93E-04	1,39E-01
2,48E-07	4,66E-08	3,63E-08	0,00E+00	4,51E-05	7,68E-05	1,71E-06	5,71E-03
5,08E-06	5,12E-07	1,79E-03	1,79E-03	4,95E-04	1,54E-03	1,11E-04	2,73E-02
5,57E-05	5,59E-06	1,96E-02	1,96E-02	5,40E-03	1,47E-02	1,22E-03	2,67E-01
1,52E-05	1,43E-06	5,02E-03	5,01E-03	1,38E-03	7,92E-03	2,96E-04	8,40E-02
4,21E-09	1,72E-09	1,24E-09	0,00E+00	1,66E-06	1,87E-04	5,84E-08	1,06E-03
3,36E-01	1,15E-02	2,03E-02	0,00E+00	1,11E+01	6,49E+01	9,55E-01	4,48E+02
1,60E-04	4,01E-05	6,52E-05	0,00E+00	3,88E-02	4,02E+01	3,06E-03	5,74E+01

Inland transport	Waste transportation	Waste	Emission	Outland transportation	Interfloor	Waste	Total
3,32E-03	1,44E-03	1,27E-03	2,75E+00	7,15E-02	8,95E-01	7,35E-02	1,03E+01
3,31E-03	1,43E-03	1,27E-03	2,75E+00	7,14E-02	9,73E-01	7,34E-02	1,04E+01
2,72E-06	5,96E-07	1,43E-06	0,00E+00	1,84E-05	-7,90E-02	8,24E-05	-4,92E-02
1,33E-06	5,38E-07	2,86E-07	0,00E+00	5,21E-05	2,80E-04	1,65E-05	2,81E-02
5,43E-09	3,58E-10	6,30E-10	0,00E+00	1,42E-08	1,82E-08	3,63E-08	1,09E-06
3,96E-05	4,57E-06	9,94E-03	9,93E-03	2,32E-03	2,30E-03	7,20E-04	6,47E-02
2,48E-07	9,32E-08	7,26E-08	0,00E+00	2,34E-06	3,43E-05	4,18E-06	8,59E-04
5,08E-06	1,02E-06	1,79E-03	1,79E-03	5,71E-04	2,14E-04	2,72E-04	1,41E-02
5,57E-05	1,12E-05	1,97E-02	1,96E-02	6,35E-03	2,18E-03	2,99E-03	1,52E-01
1,52E-05	2,85E-06	5,02E-03	5,01E-03	1,55E-03	1,00E-03	7,26E-04	3,84E-02

INNOVATIVE MATERIALS FOR A MORE SUSTAINABLE TEXTILE INDUSTRY: BIO-BASED POLYMERS AND RECYCLED FIBERS – A SHORT REVIEW

Fabrizio Cavani, Tommaso Tabanelli**

1. Introduction: The impact of the textiles industry

Today, the textile system operates in an almost completely linear way: large amounts of non-renewable resources are extracted to produce clothes that are often used for only a short time, after which the materials are mostly sent to landfill or incinerated. Indeed, the number of times a garment is worn before its end-of-life has decreased by over 35% in the period 2000-2015, a consequence of the so-called fast fashion trend.

Concerning the consumption of resources, it was close to 100 million tons of fossil oil in 2015 and is expected to become three times as much by 2050, with an impressive increase of the share of CO_2 emitted by industry from 2% until 26%, and a several million tons amount of added microfibers in the oceans (Ellen MacArthur Foundation, 2017). Emissions of CO_2 occur during the oil-based production of fibers and clothing and during their use and after use. An intensive use of chemicals is required to produce textiles, including substances of concern; these substances often remain in the manufact, and this also raises concerns because of adverse effects they can have. Chemicals used in the production and processing of textiles include solvents, surfactants, pigments, plasticizers, water and stain repellents, flame retardants and biocides (Chemsec, 2024). All this, in a scenario that foresees an increase of the production of textiles by over the 60% in the next 5-6 years.

In Europe, the consumption of textiles has the fourth highest impact on the environment and climate change, after food, housing, and mobility; moreover, textile production is the third sector for water and land use, and heavily impacts for the use of raw materials and for greenhouse gas emissions. The recycling of waste textiles still is in its infancy, being less than 1% recycled. Negative impacts are also on resources, water, and energy

**Department of Industrial Chemistry "Toso Montanari", Alma Mater Studiorum - University of Bologna, Italy*

consumption; overall, the environmental impact of textiles is very high.

2. The European initiatives

Considering all this, the European Commission is addressing the main challenges of the textiles sector as part of the *European Green Deal* and has presented its strategy to make textiles more durable, repairable, reusable, and recyclable. In the "EU strategy for sustainable and circular textiles," critical issues such as fast fashion, textile waste, and destruction of the unsold textiles are dealt with, and solutions are envisaged. Furthermore, it is claimed that the production of textile should take place in respect of sustainability targets and social rights as well (Interreg Europe, 2022).

According to the EU vision, textiles should be long-lived and recyclable, made at least in part with recycled fibers, and should not contain any hazardous substance. The issue of quality of textiles is also addressed, in contrast to the fast fashion; specific measures include Eco-design for Sustainable Products Regulation ESPR, a guideline for designing products with environmental considerations (for example, with a mandatory inclusion of recycled fibers), a Digital Product Passport with information on, e.g., circularity, and a Producer Responsibility Scheme. Currently, the focus of ESPR is on biodegradation and circular economy; biodegradation addresses the environmental impact of materials and circular economy promotes resource efficiency and minimization of waste.

The environmental impact of microplastics released from textiles is also addressed, with specific measures. Textiles made of synthetic fibers, such as polyester and acrylic, are one of the main sources of unintentional release of microplastics into the environment.

In an economy based on circularity, clothes, if not recyclable, should be made from bio-based materials, and should be biodegradable, which is not the case for most textiles nowadays. Biological cycles via composting and anaerobic digestion should be the most desired option for synthetic fibers. Cellulose-based fibers (cotton, viscose, lyocell) are naturally biodegradable, but

clothes often contain other non-biodegradable materials and compounds. When biodegradable fibers (such as cellulose-based fibers or wool) are mixed with non-biodegradable fibers (such as polyester, acrylic, nylon, or elastane), the resulting yarn of this mix is not biodegradable. This creates an issue, as blending of different types of fibers is a common practice, aimed at providing improved properties to the manufacture. Worth note, despite the cultivation of cotton accounting for less than 3% of land, it requires more than 15% of all pesticides used.

Digitalization may help textiles producers search for substitution of unsafe chemicals with safer ones. For example, the ZDHC Chemical Gateway provides information on how marketed chemicals conform with the Manufacturing Restricted Substances List, MRSL (ZDHC Foundation, 2024).

According to the EU vision, a new model for textiles economics should include the following targets:

1. Phase out substances of concern and microfibers release. Each year, around half a million tons of plastic (polyester, acrylic, and nylon) microfibers resulting from the washing of textiles are estimated to be released into the ocean.
2. Increase clothing utilization.
3. Improve recycling of used clothes. Currently, technologies for the recycling of both cellulose-based and plastic-based fibers, such as polyesters and polyamides, are either already available, or close to being implemented, often relying on the use of proper solvents. But in many cases industries are reluctant in industrialization of new technologies because of the high risk associated (high costs for both CAPEX and OPEX). Chemical recycling of cotton is already commercial, and technologies are being developed for blends of cotton with plastic fibers. Depolymerization of the synthetic polymer to the starting monomers is currently practiced for polyamides; monomers can be used to produce new polymers. As an example, in 2021 Tomra and Stadler delivered a fully automated sorting plant in Malmö (Sweden), with a capacity of up to 4.5 tonnes/hour in one line. The incoming material includes pre- and post-consumer waste. The former consists of dry, industrial waste from textile producers such as clippings, yarn and rejects, the latter of clothing

and household textiles, including unsorted material from separate collection and manually pre-sorted and industrial waste from textile leasing and rental services. The material is sorted all and may contain buttons, zippers and other non-textile parts (Tomra, 2021).

4. Move to renewable resources and raw materials (low-C materials) for the production of virgin fibers. Which means not only replace fossil-based feedstock with biomass from regenerative agriculture, but also improve the efficiency of current production technologies, so to generate less waste (such as offcuts), and hence need less feedstock, reduce water use, reduce energy needs (which ideally should also be renewable).
5. Some chemicals manufacturers, in collaboration with textiles and garment factories, are now producing renewables-based compounds for dyes and textiles manufacturing. Relevant examples in Italy of chemical companies producing polymers for fibers and active in the development of new textile materials based either on biopolymers or on recycled fibers are RadiciGroup and Aquafil.
6. Biofeel® Eleven, produced by RadiciGroup, is a 100% bio-based yarn made from polyamide 11 and is part of the Biofeel® family, which consists of yarns derived from renewable sources. RadiciGroup is the only European manufacturer of this yarn, which features specific characteristics such as low water absorption, increased lightness, and greater abrasion resistance. Alongside products obtained from renewable sources, RadiciGroup is committed to the recycling of post-industrial materials, coming from the recovery of industrial waste generated during the manufacturing process, and post-consumer, derived from products that private individuals, commercial, industrial and institutional structures they can no longer be used for their intended purpose. An example is Renycle®, a range of sustainable polymers, obtained from the recycling of post-industrial and post-consumer polyamide to meet the growing needs of the market in terms of products with low and measurable environmental impact, without sacrificing quality, reliability, traceability, safety (RadiciGroup, 2024).

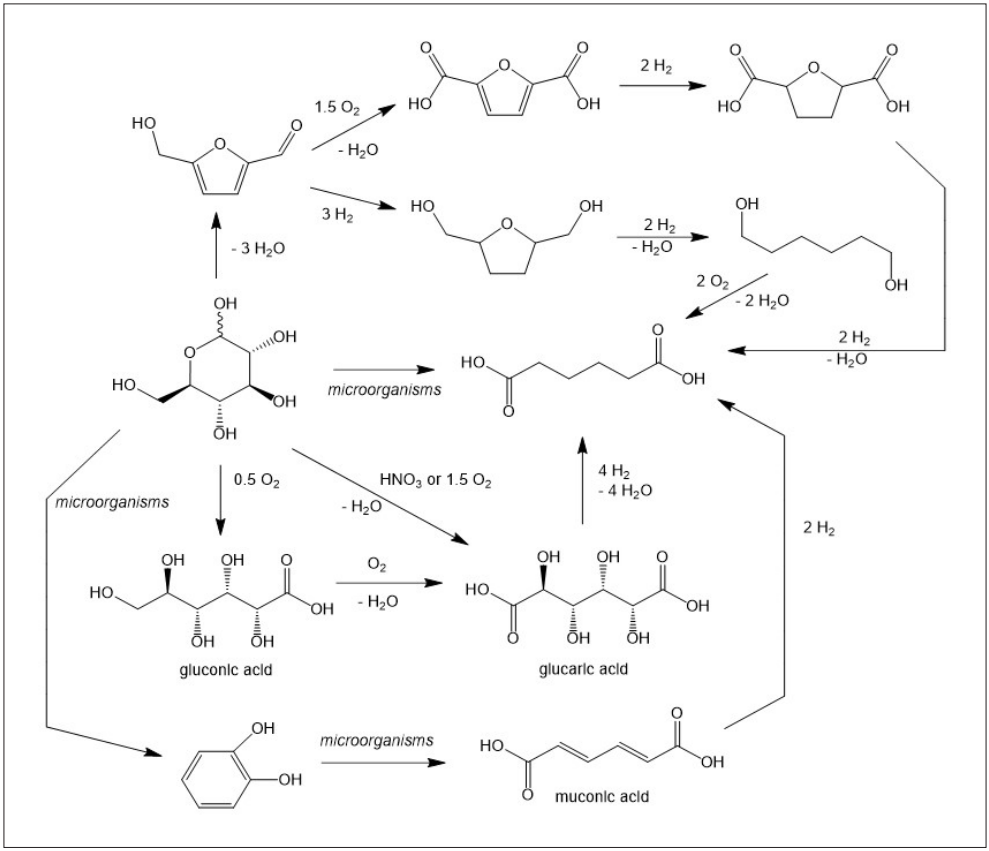
7. In Aquafil, nylon waste—such as fishing nets, fabric scraps, carpet flooring and industrial plastic is recovered and converted into new yarn, which has the same qualitative characteristics as traditional nylon. The flagship product of Aquafil is ECONYL® regenerated nylon (Aquafil, 2022).

3. Petroleum or renewables for fibers production?

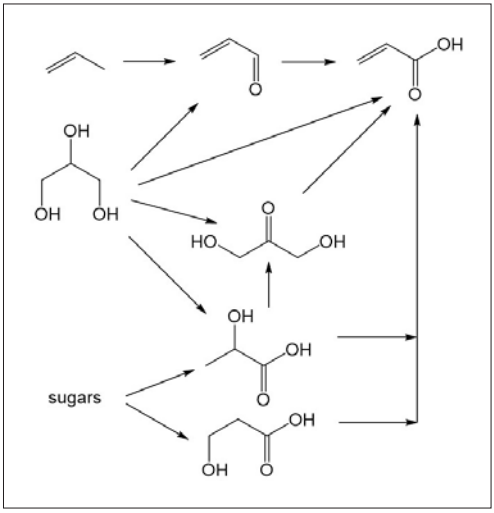
The prevailing materials for fibers production are polyester, polyamides and cotton. The production of polyesters requires chemicals, typically obtained from fossil-based raw materials, and requires a large amount of energy. On the other hand, the production of cotton fibers requires large amounts of chemicals. Polyester production for textiles is responsible for the emission of several hundred million tons of CO_2 equivalent (Kirchain et al., 2015). The solution is the use of renewable feedstock for plastic-made fibers and the use of regenerative agriculture for cellulose-based fibers, which means avoiding the use of synthetic pesticides or fertilizers, and sourcing cellulose from fast-growing plants which are not grown in land used for agriculture for food production. An alternative option is the use of waste from, e.g., food industry. Examples are the SME Orange Fiber (Orange Fiber, 2024), which uses waste from orange juice production to make fibers. Similar approaches are used by Qmilk (2024) and AgraLoop™ (2024).

Amongst the polymers for fibers obtained from fossil-sources building blocks, some are bio-degradable, some are not. This is the case of selected polyesters, which can be hydrolysed at the end of life to the original monomers, and the latter can be degraded by micro-organisms or enzymes; an example is polyglycolic acid (Samantaray et al., 2020; Kumar et al., 2021). Also, poly(butylene adipate-co-terephthalate) is biodegradable; it can be hydrolysed by bacteria, and the monomers are degradable (Ferreira et al., 2019; Jian et al., 2020); it is considered one of the most promising polymers for sustainable materials. Another example is polycaprolactone. Conversely, there are several polymers which are either not degradable at all or very slowly degradable; this is the case for most polyesters, polypropylene and polyamides (Nylon).

Polylactic acid (PLA) fiber is a polyester hydrolysable and degradable by microorganisms. Indeed, PLA is recognized as the most significant bio-based material and is used in food packaging, textiles, and others. Polyhydroxyalkanoates (such as polyhydroxybutyrate, the most common, but also polyhydroxo fatty acids in general) are intracellular polyesters synthesized by various microorganisms and are decomposed by microorganisms in various natural environments (soil, composting, even in seawater) (Meereboer et al., 2020). Conversely, there are biopolymers which are hardly biodegradable or are not degradable at all. For example, highly crystalline polymers may be difficult to degrade (Zambrano et al., 2020). An example is polypropylene terephthalate, a polyester which indeed is only in part bio-based, since propylene glycol can be synthesized starting from glycerol or other bio-based molecules, but terephthalic acid is still made from *p*-xylene, the latter being obtained from naphtha reforming. Nowadays, the aim is the synthesis of bio-based polymers for fibers, which are synthesized from non-food, second generation crops, ideally from residues to better fit the circular economy principles and are fully degradable within a reasonable lapse of time. This because the production of bio-based materials from food crops has led to food shortages in some countries. Lignocellulose, such as corn stalks, is the preferred raw material for the synthesis of 2nd generation bio-based building blocks (Deutschmann & Dekker, 2012; Tian et al., 2022). Lignocellulose is then fragmented into its main components, cellulose, hemicellulose and lignin, and each one of the three fractions undergoes separate, specific down-stream treatment to be de-structured and transformed into the corresponding monomers, which after purification may finally become the building blocks for virgin biopolymers. These transformations may be either biological or chemo-catalytic, as illustrated in fig. 1, reporting the different pathways for obtaining adipic acid, the co-monomer for Nylon 6,6, starting from glucose (Solmi et al., 2017). Similarly, also adipic acid esters (e.g. dimethyl adipate) has been recently obtained by reacting hemicellulose-derived cyclopentanone and dimethyl carbonate, with good yields by the use of innovative and recyclable heterogeneous catalysts (Galletti et al., 2025). A similar scheme pertains the synthesis of acrylic acid (fig. 2), the monomer for acrylates, in this case



1. The different pathways for the synthesis of bio-adipic acid, monomer for Nylon 6,6.



2. The different pathways for the synthesis of bio-acrylic acid.

with different C3 bio-based building blocks as the starting molecule (Chieregato et al., 2017; Chieregato et al., 2015).

Cellulose fibers are leading the pathway in replacing single-use plastics. Fully cellulose-based textiles from novel and recycled fibers are already available. The market of manufactured cellulosic fibers (MMCF) has been growing in waves in order to adapt to the new markets from China to Latin America. The next wave of growth will be based on textile from waste and agricultural residues, new value chains driven by reduced reliance on cotton and technical advancements in MMCF technologies. In support of all this, manufacturing costs for dissolving wood pulp are decreasing.

Concerning the so-called third generation bio-based raw materials, which indeed also include CO_2, fiber yarns are now made using thermoplastic polyurethane (Covestro, 2024). The melt spinning technology allows avoiding the use of unfriendly solvents, which are used instead in dry spinning to produce elastic synthetic fibers.

4. Recent advancements in the synthesis of fibers for textiles: A few examples

We now report some examples of recent achievements reported by enterprises, regarding initiatives to produce bio-based fibers and recycle of end-of-life fibers for textiles.

Avantium N.V., a leading company in renewable polymer materials, recently announced a strategic collaboration with leading textile innovators Auping, Monosuisse and Antex. This partnership aims to develop polyethylfuranoate (PEF)-based yarns, to be used in mattresses for Auping; this initiative demonstrates the introduction of PEF to the everyday life of consumers (van Reedt Dortland, 2024).

Valmet, a company with expertise in fiber processing, aims at developing and commercializing novel process concepts for novel cellulose-based textile fibers. The availability of piloting facilities enables demonstration, scaling-up and mitigation of risks (Kangas, 2024).

Hyosung TNC is partnering with Ambercycle, to advance the commercialization of innovative materials. The target is to

introduce in South Korea a textile-to-textile, circular polyester, cycora®, into brand supply chains. A circular textile system aims at repurposing the end-of-life products into fibers for brands willing to decrease their environmental impact (Ambercycle, 2024).

The assets of Renewcell, expert in cotton textile recycling, have been acquired by Altor, an investment firm based in Sweden; the company has been renamed Circulose. The technology of recycling cotton to make a dissolving pulp for MMCF producers, such as viscose, has been a cornerstone of the company's operations (Altor, 2024).

The start-up re.solution, based in Aachen and winner of the ACHEMA Start-up Award 2024, recycles textiles containing polyester using a process with renewable energy and lower water and chemical consumption compared to similar technologies. The process is claimed to be economically competitive compared to polyester's fossil route (ACHEMA, 2024).

BASF is now offering polyamides PA6 and PA6.6 product range for textile applications according to Recycled Claim Standard (RCS) (Ultramid® Ccycled®). This label enables manufacturers to market certified textiles that have been produced using recycled raw materials. The production is based on the chemical recycling of plastic waste that is difficult to recycle, such as used tires, and certified using a mass-balance approach.

To promote the acceptance of chemical recycling in the textile industry, BASF has been working with the standards of Textile Exchange since 2020, one of the leading non-profit organizations in the field of recycled raw materials certification for the textile industry. Moreover, BASF is also offering loopamid®, the first circular PA6 based entirely on textile waste, and Ultramid® Biomass Balance (BMB), a drop-in concept that enables the use of biowaste raw materials in product manufacturing (Scheurer, 2024).

The Lenzing Group, a supplier of regenerated cellulose fibers for the textile industry, is working with the non-profit organisation RTDS Group and other partners from research and industry to promote the scaling of lyocell filaments. By optimising the production process and intermediate processing steps, the aim is to replace synthetic fibers with environmentally friendly lyocell filaments in recyclable end applications (Köfner, 2024).

References

ACHEMA, 2024
ACHEMA. (2024, December 6). *On to the top of the podium with textile recycling: re.solution wins ACHEMA Start-up Award 2024*. https://www.achema.de/en/press/press-releases/article/on-to-the-top-of-the-the-podium-with-textile-recycling-resolution-wins-achema-start-up-award-2024

AgraLoopTM, 2024
AgraLoop™. (2024). https://circularsystems.com/agraloop

Altor, 2024
Altor. (2024, June 4). *Altor acquires remaining assets of Renewcell, ushering in a new era as Circulose*. https://www.renewcell.com/en/altor-acquires-remaining-assets-of-renewcell-ushering-in-a-new-era-as-circulose/

Ambercycle, 2024
Ambercycle. (2024, June 12). *Ambercycle and Hyosung TNC join forces to scale decarbonized, circular polyester*. https://www.prnewswire.com/news-releases/ambercycle-and-hyosung-tnc-join-forces-to-scale-decarbonized-circular-polyester-302169879.html

Aquafil, 2022
Aquafil. (2022). *ECONYL® nylon*. https://www.aquafil.com/environment/

Chemsec, 2024
Chemsec. (2024). *Textiles come with a toxic footprint*. https://textileguide.chemsec.org/find/textiles-come-with-a-toxic-footprint/.

Chieregato et al., 2015
Chieregato, A., Dolores Soriano, M., Garcia-Gonzalez, E., Puglia, G., Basile, F., Concepcion, P., Bandinelli, C., Lopez Nieto, J. M., & Cavani, F. (2015). Multielement crystalline and pseudocrystalline oxides as efficient catalysts for the direct transformation of glycerol into acrylic acid. *ChemSusChem*, *8*, 398–406. https://doi.org/10.1002/cssc.201402721

Chieregato et al., 2017
Chieregato, A., Bandinelli, C., Concepcion, P., Dolores Soriano, M., Puzzo, F., Basile, F., Cavani, F., & Lopez Nieto, J. M. (2017). Structure–reactivity correlations in vanadium-containing catalysts for one-pot glycerol oxidehydration to acrylic acid. *ChemSusChem*, *10*, 234–244. https://doi.org/10.1002/cssc.201600954

Covestro, 2024
Covestro. (2024). https://solutions.covestro.com/en/materials

Deutschmann & Dekker, 2012
Deutschmann, R., & Dekker, R. F. (2012). From plant biomass to bio-based chemicals: Latest developments in xylan research. *Biotechnol. Advances*, *30*(6), 1627–1640. https://doi.org/10.1016/j.biotechadv.2012.07.001

Ellen MacArthur Foundation, 2017
Ellen MacArthur Foundation. (2017). *A new textiles economy: Redesigning fashion's future*. http://www.ellenmacarthurfoundation.org/publications

Ferreira et al., 2019
Ferreira, F. V., Cividanes, L. S., Gouveia, R. F., & Lona, L. M. (2019). An overview on properties and applications of poly (butylene adipate-coterephthalate)–PBAT based composites. *Polymer Engineering and Science*, *59*(2), E7-E15. https://doi.org/10.1002/pen.24770

Galletti et al., 2025
Galletti, G., Allkanjari, D., Manna, A., Valzano, E., Monti, L., Dimitratos, N., De Maron, J., Cavani, F., Tabanelli, T. (2025). Zinc-based oxides as alternative cheap and stable catalysts for the production of adipates from cyclopentanone and dimethyl carbonate. *Sustainable Chemistry and Pharmacy*, *45*, 102018. https://doi.org/10.1016/j.scp.2025.102018

Interreg Europe, 2022
Interreg Europe. (2022, May 30). *New EU Strategy for sustainable and circular textiles*. https://www.interregeurope.eu/policy-learning-platform/news/new-eu-strategy-for-sustainable-and-circular-textiles

Jian, Xiangbin & Xianbo, 2020
Jian, J., Xiangbin, Z., & Xianbo, H. (2020). An overview on synthesis, properties and applications of poly (butylene-adipate-co-terephthalate)–PBAT. *Advanced Industrial and Engineering Polymer Research*, *3*(1), 19–26. https://doi.org/10.1016/j.aiepr.2020.01.001

Kangas & Norstedt, 2024
Kangas, H. & Norstedt, A. (2024, May 13). *Going towards the 4th wave of growth. Insights and trends from Cellulose Fibers Conference 2024*. https://www.valmet.com/insights/blogs/going-towards-the-4th-wave-of-growth/

Kirchain et al., 2015
Kirchain, R., Olivetti, E., Miller, T. R., & Greene, S. (2015, September 22). *Sustainable apparel materials*. https://search.issuelab.org/resources/29099/29099.pdf

Köfner, 2024
Köfner, D. (2024, July 31). *Lenzing forces reformation of the textile value chain*. https://www.lenzing.com/newsroom/press-releases/press-release/lenzing-forces-reformation-of-the-textile-value-chain

Kumar, et al., 2021
Kumar, A., Mir, S. M., Aldulijan, I., Mahajan, A., Anwar, A., & Leon, C. H. … (2021). Load-bearing biodegradable PCL-PGA-beta TCP scaffolds for bone tissue regeneration. *J. Biomed. Mat. Res.*, *109*(2), 193–200. https://doi.org/10.1002/jbm.b.34691

Meereboer, Misra & Mohanty, 2020
Meereboer, K. W., Misra, M., & Mohanty, A. K. (2020). Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their composites. *Green Chemistry*, *22*(17), 5519–5558. https://doi.org/10.1039/d0gc01647k

Orange Fiber, 2024
Orange Fiber. (2024). https://orangefiber.it/

Qmilk, 2024
Qmilk. (2024). https://www.qmilkfiber.eu/?lang=en

RadiciGroup, 2024
RadiciGroup (2024). https://www.radicigroup.com/en/sustainability

Samantaray et al., 2020
Samantaray, P. K., Little, A., Haddleton, D. M., McNally, T., Tan, B., & Sun, Z. … (2020). Poly(glycolic acid) (PGA): A versatile building block expanding high performance and sustainable bioplastic applications. *Green Chemistry*, *22*(13), 4055–4081. https://doi.org/10.1039/d0gc01394c

Scheurer, 2024
Scheurer, H. (2024, April 22). *BASF now offering polyamides for the textile industry according to Recycled Claim Standard (RCS)*. https://www.basf.com/global/en/media/news-releases/2024/04/p-24-186

Solmi et al., 2017
Solmi, S., Morreale, C., Ospitali, F., Agnoli, S., & Cavani, F. (2017). Oxidation of d-Glucose to glucaric acid using Au/C catalysts. *ChemCatChem*, *9*(14), 2797–2806. https://doi.org/10.1002/cctc.201700089

Tian et al., 2022
Tian, W., Huang, K., Zhu, C., Sun, Z., Shao, L., Hu, M., & Feng, X. (2022). Recent progress in biobased synthetic textile fibers. *Frontiers in Materials*, *9*, 1098590. https://doi.org/10.3389/fmats.2022.1098590

TOMRA Recycling, 2021
TOMRA Recycling. (2021, February 23). *TOMRA and STADLER deliver world's first automated textile sorting plant*. https://www.tomra.com/en/waste-metal-recycling/media-center/customer-stories/sysav-industri-ab

van Reedt Dortland, 2024
van Reedt Dortland, C. (2024, July 17). *Avantium partners with leading textile innovators to create PEF fabrics for Auping mattresses*. https://newsroom.avantium.com/avantium-partners-with-leading-textile-innovators-to-create-pef-fabrics-for-auping-mattresses/#

Zambrano, Pawlak & Venditti, 2020
Zambrano, M. C., Pawlak, J. J., & Venditti, R. A. (2020). Effects of chemical and morphological structure on biodegradability of fibers, fabrics, and other polymeric materials. *BioResources*, *15*(4), 9786–9833. https://doi.org/10.15376/biores.15.4.zambrano

ZDHC Foundation, 2024
ZDHC Foundation. (2024). *Safer Chemicals*. Roadmap To Zero - Input.

USE OF RECYCLED CERAMIC AS CEMENT SUBSTITUENT FOR A CIRCULAR MADE-IN-ITALY FURNITURE INDUSTRY

Lucia Ferrari, Elisa Franzoni**

1. Introduction

On a worldwide basis, the revenue in the furniture market amounts to US$729.20bn in 2023, being expected to annually grow by about 5% (CAGR 2023-2028) (Università di Bologna, 2023). Inside this market, the role of furniture made of concrete and cement-based materials is continuously growing and becoming more creative (Krichels, 2013), as more and more designers and customers realize the possibilities offered by this material for custom furniture pieces (Peterson, 2002). In fact, concrete furniture design is rapidly evolving, and designers have found new ways to create much more elegant looking 3-dimensional shape furniture that whilst much thinner in form is still incredibly strong, also suitable for contemporary homes and for creating, for example, a more organic, Nordic feel (Maxi Readymix Concrete, 2019). The design of furniture made of cement-based materials was also boosted by the possibility of manufacturing them by 3D printing, allowing to achieve a variety of interesting shapes (Özalp & Yilmaz, 2020; Šál & Dědič, 2020; Sertoglu, 2021). Moreover, specific benefits can be achieved by using concrete in outdoor furniture, such as the resistance to harsh climates (Mulyono et al., 2017) or the achievement of smart functionalities (Faneca et al., 2020).

Given the importance of this industrial sector and the growing consumers' awareness of the sustainability goals, the global market of eco-friendly furniture is expected to expand at a compound annual growth rate (CAGR) of 8.6% from 2022 to 2030. Despite this, the development of sustainable cement-based furniture objects is still lacking. This project is aimed at the development of digitalized mix-design procedures for the manufacturing of sustainable furniture materials based on low-carbon binders.

**Department of Civil, Chemical, Environmental, and Materials Engineering, Alma Mater Studiorum - University of Bologna, Italy*

On one hand, Limestone Calcined Clay Cement (LC^3) was proposed as a new low-carbon blended cement that allows cement manufacturers to reduce the environmental impact of cement production (Scrivener et al., 2018). The reduced clinker content lowers CO_2 emissions from limestone in the raw materials (by up to 40% compared to OPC) and decreases the fuel required for clinker burning (WBCSD, 2009). Significant energy savings are achieved because calcined clays are softer for grinding and are heated at approximately 700-800 °C, whereas the manufacture of clinker requires a temperature of 1400-1500 °C (Scrivener et al., 2018).

On the other hand, in Italy, the traditional ceramic manufacturing process generates residual powders during various stages, which can be repurposed as potential cement substitutes (Boschi et al., 2020). These ceramic waste materials, including scraps, waste powders, sludge, and tile residues, have properties that make them effective binders in construction materials, offering both performance and sustainability benefits (European Commission-BRITE, 2007). Ceramic by-products have been successfully used in concrete as recycled aggregates (Juan-Valdés et al., 2021; Medina et al., 2016) and reinforcing agents (Seymour et al., 2022), and as cement substitutes in mortar (Awoyera et al., 2017; Lavat et al., 2009). Furthermore, discarded ceramic powders may exhibit pozzolanic properties, promoting their use as supplementary cementitious materials (Ferrara et al., 2019; Jacoby & Pelisser, 2015). Research has demonstrated that ceramic waste can interact chemically with portlandite to form calcium silicate hydrate and calcium silico-aluminate hydrate, highlighting its pozzolanic potential (Dos et al., 2021). Incorporating recycled ceramics into cement-based materials has shown significant potential in enhancing resistance to harsh environments, such as improved resistance to chemical attacks, reduced alkali-silica reactions (Bignozzi & Saccani, 2012), better resistance to chloride penetration (Siddique et al., 2019), reduced carbonation (Ogawa et al., 2020), and overall improved durability (Alsaif, 2021). Life Cycle Analysis (LCA) highlighted that utilizing recycled ceramics in construction materials, like concrete, not only enhances performance and reduces environmental impact but also helps conserving natural resources,

thereby lowering material depletion and the associated ecological footprint (Chen et al., 2022).

Although the literature shows the interest in using ceramic wastes as pozzolanic material in cementitious mixes, even leading to improved performances, only one very recent study was found about the introduction of by-products from ceramic industry in LC^3 preparation (Mohit et al., 2023). The capability of ceramic waste in crafting a ternary cement blend comprising Portland cement, ceramic waste powder, and limestone—composed of 75% OPC, 15% ceramic waste, and 10% limestone—was substantiated through the demonstration of enhanced mechanical strength compared to the reference cement at both 28 and 90 days. This confirms the progress beyond the state-of-the-art, the innovation and the industrial benefit potentially deriving from the development of the materials proposed in the present project.

This study explores the benefits of using recycled ceramics in low-carbon cement, specifically LC^3, with the aim of providing solutions for urban furniture applications. The analysis of two types of ceramic waste powders was conducted to determine the key factors affecting the final material properties. LC^3 made with Calcined Clay (CC) served as a reference point for comparing the recycled ceramics (RC1 and RC2). To evaluate these binders, the mortar's flow properties using a flow table test was measured. Additionally, Time-Domain Nuclear Magnetic Resonance (TD-NMR) was involved to determine the water availability in the paste during hydration. Colour analysis on hardened paste was also performed and mechanical strength test after 2 days confirmed that recycled ceramics can effectively replace CC in LC^3, enhancing the sustainability and performance of the Italian industry.

2. Experimental

2.1. Materials

Two types of ceramic waste were selected and analyzed: one from tile rectification (Atlas Concorde, Fiorano Modenese (MO), Italy) and the other from unfired roof tiles (Industrie Cotto Possagno, Possagno (TV), Italy). These ceramic wastes,

labeled RC1 and RC2, were used in their raw form without any pre-treatment. For the preparation of LC^3, commercially available CEM I 52.5 R, Limestone (LS), and Calcined Clay (CC) were used, maintaining a clinker content of 50% by mass and a CC ratio of 2:1 by mass. In the formulation of LC^3, CC was replaced by RC1 and RC2 based on mass, as shown in table 1.

Tab. 1. Formulation of LC^3 in mass%.

Label	LC3-CC	LC3-RC1	LC3-RC2
CEM I (%)	52.6	52.6	52.6
Limestone (%)	15.8	15.8	15.8
CC (%)	31.6	-	-
RC1 (%)	-	31.6	-
RC2 (%)	-	-	31.6

Measurements by X-Ray Diffraction (XRD) and quantification by Rietveld refinement enabled to detect the mineralogical composition of CEM I: 61% C3S, 8.2% C2S, 6.0% C3A, 11% C4AF, 5.1% calcium sulfate (sum of anhydrite, hemihydrate and dihydrate), 3.2% calcite, 1.4% arcanite, 1.2% portlandite, 0.64% dolomite and 2.2% of other minor elements.

Powders' densities and granulometric properties of materials are reported in table 2, as well as Specific Surfare area (SSA) and Specific Pore Volume (SPV) measured by physical adsorption of nitrogen molecules on the solid surface (BET method).

Tab. 2. Material densities and granulometric properties (d10 indicates the particle size at which 10% of the material is finer, in analogy is the same for d50 and d90).

Samples	CEM I	LS	CC	RC1	RC2
Density (g/cm^3)	3.07	2.72	2.7	2.61	2.82
d10 (µm)	2.11	4.82	2.39	3.89	1.21
d50 (µm)	11.1	30	17.1	26.9	6.33
d90 (µm)	32.4	135	55.1	92	31.3
SSA (m^2/g)	0.6	0.06	48	0.9	28
SPV (cm^3/g)	0.0034	0.0062	0.1084	0.003	0.0397

The materials' densities were as expected. RC2 had a similar particle size distribution to CEM I but with more fine particles, while CC, RC1, and LS had coarser particles. CC had the highest specific surface area (SSA) and pore volume, followed by RC2 and then RC1.

Mortar was prepared using the EN 196-1 standard composition, with natural crushed sand (max diameter 4 mm) instead of standard sand. A polycarboxylate ether-based superplasticizer (SP) was added at 0% and 1% to test its impact on workability. Pastes were made with a 0.4 water-to-cement ratio using deionized water in a stirring mixer.

2.2. Methods

2.2.1. Tests in mortars

Two fixed dosages of superplasticizer were used to evaluate mortar workability by flow table test according to standard EN 1015-3 (British Standards Institution et al., n.d.) and the average mortar diameter was measured. Mechanical compressive strength was measured at 2 days on specimens without superplasticizer according to the standard EN 197-1 (European Committee for Standardization & British Standards Institution, 2007).

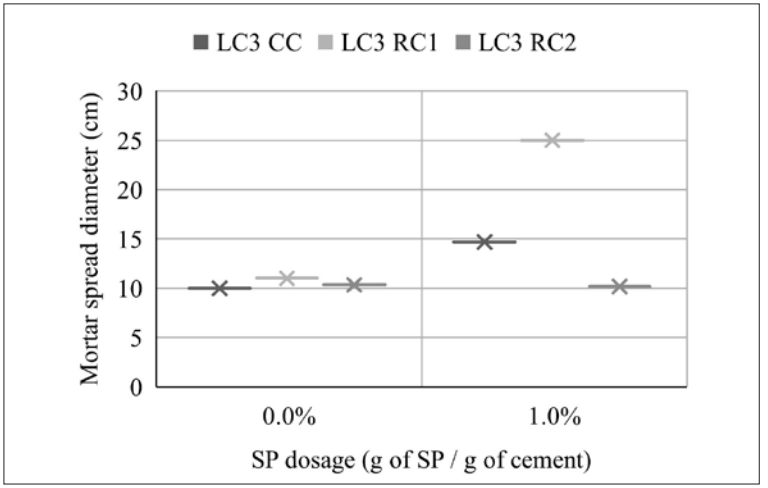
2.2.2. Tests on paste

Colorimetric assessment was performed on hardened paste, prepared with LC3-CC, LC3-RC1 and LC3-RC2 at a water-to-binder ratio of 0.4. The pastes were analyzed after 7 days of hardening and 24 hours of drying at 110°C, with a spectrophotometer, NH310 Portable Colorimeter, from 3nh company (Guangzhou, P.R. China). For each sample, five acquisitions were collected on five different points of the surface and the average is reported in the results part.

3. Results

3.1. Fresh properties

Figure 1 shows the rheological results of mortar workability at two dosages of SP.



1. Results of flow table test according to EN 1015-3 (European Committee for Standardization & British Standards Institution, 2007).
All images are reproduced in color in the online edition of the book.

Measurements with the flow table test revealed varying behaviors based on the superplasticizer dosage. At 0% superplasticizer, the mortar was extremely viscous and thick across all cement formulations. The initial diameter of 10 cm remained almost unchanged after 15 drops of the flow table disc, indicating that the fresh mortar's consistency prevents any deformation under this type of stress. In contrast, with 1% superplasticizer, the mortar's behavior differed significantly among pozzolanic materials. The mortar made with LC3-RC1 flowed easily, reaching a diameter of 25 cm without vertical impacts. The mortar made with LC3-CC (the reference) spread to about 15 cm after 15 drops. However, the mortar made with LC3-RC2 remained unchanged, maintaining a diameter of 10 cm even after the application of the vertical stress. These results show that the response to superplasticizer varies greatly depending on the pozzolanic powder used.

Given the significant variability in specific surface area (SSA) and particle size of CC and recycled ceramics, the particles' ability to adsorb the superplasticizer also varies. RC1, with an SSA of approximately 1 m^2/g and d90=92.0 μm, quickly saturates all available adsorption sites with organic molecules at a 1% dosage of superplasticizer, resulting in a highly fluid mortar. RC2, with an SSA of approximately 28 m^2/g and d90=31.3 μm, requires a higher dosage of superplasticizer to saturate its surface, and its fine particles negatively impact rheological properties, making

the superplasticizer ineffective at a 1% dosage. CC, with an SSA of about 48 m^2/g and d90=55.1 μm, provides an intermediate effect as its particle size falls between RC1 and RC2, yielding a satisfactory effect with the superplasticizer used.

Overall, particle size appears to influence the effect of the superplasticizer more than SSA values. For a deeper understanding of this effect, the possible impact of the zeta potential of different powders' surfaces is currently under investigation.

3.2. Hardened properties

The colorimetric analysis of hardened pastes was conducted to evaluate the aesthetic and practical implications of using ceramic waste in the final material. The results are presented in table 3, using the L*a*b* color scale. In this scale, L measures lightness, with values ranging from 0 (black) to 100 (white); a indicates the range from green to red, with values from -128 to +127; and b measures the spectrum from blue to yellow, also ranging from -128 to +127. Additionally, table 3 includes the compressive strength data for mortar without superplasticizer.

Tab. 3. Colorimetric analysis of hardened pastes (L*a*b* scale) and compressive strength measured on mortar at 2 days.

Samples	LC3-CC	LC3-RC1	LC3- RC2
L	54.82	69.09	68.02
a	9.32	-0.16	0.59
b	13.8	3.06	5.54
Actual color			
Compressive Strength (MPa)	15.4	12.9	18

In terms of color analysis, recycled ceramic from tile rectification, having initially a white or gray color, results in a hardened paste with a final hue similar to a typical cementitious sample, exhibiting values of L=62.17, a=-0.37, and b=3.12. In contrast, the reference CC used in this study has a reddish tint due to ferritic impurities, which might be interesting for applications requiring a specific color or aesthetic quality.

Regarding compressive strength, the particle size of the ceramic powder significantly influences the properties of the hardened mortar. RC2, with its finer particle size distribution, demonstrates improved mechanical strength at 2 days compared to the reference CC. In contrast, RC1, which has larger particles, shows lower reactivity during cement hydration. This difference in performance is attributed to the higher reactivity of the finer powder.

4. Conclusions

This research explores the possibility to improve LC^3 sustainability by substituting calcined clay with ceramic wastes from tile rectification. The aim is to provide suitable materials for fabrication of urban furniture. Two types of recycled ceramics in both their fresh and hardened states were analyzed. The findings revealed that the rheological properties and superplasticizer efficiency are influenced by the powders' granulometry: finer powders negatively impact superplasticizers' ability to improve mortar fluidity. For the hardened properties, recycled ceramics offer dual benefits: the cement's color is closer to the traditional grey shade, and the finer waste particles boost mechanical performance at 2 days, unlike the coarser powder.

Future analyses will focus on determining the superplasticizer dosage needed for comparable workability and assessing how particle size and specific surface area affect rheological properties. Moreover, the performances at 28 days will be investigated to evaluate the durability properties of the formulated mortars.

References

Alsaif, 2021
Alsaif, A. (2021). Utilization of ceramic waste as partially cement substitute – A review. *Construction and Building Materials*, *300*, 124009. https://doi.org/10.1016/J.conbuildmat.2021.124009

Awoyera et al., 2017
Awoyera, P. O., Dawson, A. R., Thom, N. H., & Akinmusuru, J. O. (2017). Suitability of mortars produced using laterite and ceramic wastes: Mechanical and microscale analysis. *Construction and Building Materials*, *148*, 195–203. https://doi.org/10.1016/J.conbuildmat.2017.05.031

Bignozzi & Saccani, 2012
Bignozzi, M. C., & Saccani, A. (2012). Ceramic waste as aggregate and supplementary cementing material: A combined action to contrast alkali silica reaction (ASR). *Cement and Concrete Composites*, *34*(10), 1141–1148. https://doi.org/10.1016/J.cemconcomp.2012.07.001

Boschi et al., 2020
Boschi, G., Masi, G., Bonvicini, G., & Bignozzi, C. M. (2020). Sustainability in Italian ceramic tile production: Evaluation of the environmental impact. *Applied Science*, *10*(9063), 1–15. https://doi.org/10.3390/app10249063

British Standards Institution et al., n.d.
British Standards Institution, European Committee for Standardization. Technical Committee CEN/TC 125, M., British Standards Institution. Technical Committee B/519, M. and associated testing, & European Committee for Standardization. (n.d.). *Methods of test for masonry. Part 3, Determination of consistence of fresh mortar (by flow table)*.

Chen et al., 2022
Chen, X., Zhang, D., Cheng, S., Xu, X., Zhao, C., Wang, X., Wu, Q., & Bai, X. (2022). Sustainable reuse of ceramic waste powder as a supplementary cementitious material in recycled aggregate concrete: Mechanical properties, durability and microstructure assessment. *Journal of Building Engineering*, *52*. https://doi.org/10.1016/j.jobe.2022.104418

Dos Santos Barreto et al., 2021
Dos Santos Barreto, E., Stafanato, K. V., Teixeira Marvila, M., Rangel Garcez de Azevedo, A., Ali, M., Matheus, R., Pereira, L., & Neves Monteiro, S. (2021). Clay Ceramic Waste as Pozzolan Constituent in Cement for Structural Concrete. *Materials*, *14*(11), 2917. https://doi.org/10.3390/ma14112917

European Commission-BRITE, 2007
European Commission-BRITE. (2007). *Ceramic manufacturing industry*. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/cer_bref_0807.pdf

European Committee for Standardization, & British Standards Institution, 2007
European Committee for Standardization, & British Standards Institution. (2007). *Cement. Part 1, Composition, specifications and conformity criteria for common cements*. BSI.

Faneca et al., 2020
Faneca, G., Ikumi, T., Torrents, J. M., Aguado, A., & Segura, I. (2020). Conductive concrete made from recycled carbon fibres for self-heating and de-icing applications in urban furniture. *Materiales de Construccion*, *70*(339). https://doi.org/10.3989/mc.2020.17019

Ferrara et al., 2019
Ferrara, L., Deegan, P., Pattarini, A., Sonebi, M., & Taylor, S. (2019). Recycling ceramic waste powder: effects its grain-size distribution on fresh and hardened properties of cement pastes/mortars formulated from SCC mixes. *Journal of Sustainable Cement-Based Materials*, *8*(3), 145–160. https://doi.org/10.1080/21650373.2018.1564396

Jacoby & Pelisser, 2015
Jacoby, P. C., & Pelisser, F. (2015). Pozzolanic effect of porcelain polishing residue in Portland cement. *Journal of Cleaner Production*, *100*, 84–88. https://doi.org/10.1016/J.jclepro.2015.03.096

Juan-Valdés et al., 2021
Juan-Valdés, A., Rodríguez-Robles, D., García-González, J., Sánchez de Rojas Gómez, M. I., Ignacio Guerra-Romero, M., De Belie, N., & Morán-del Pozo, J. M. (2021). Mechanical and microstructural properties of recycled concretes mixed with ceramic recycled cement and secondary recycled aggregates. A viable option for future concrete. *Construction and Building Materials*, *270*, 121455. https://doi.org/10.1016/J.conbuildmat.2020.121455

Krichels, 2013
Krichels, J. (2013, July 26). The experimental designers making furniture out of concrete. *Financial Times*. https://www.ft.com/content/55f1979e-eefa-11e2-9269-00144feabdc0

Lavat, Trezza & Poggi, 2009
Lavat, A. E., Trezza, M. A., & Poggi, M. (2009). Characterization of ceramic roof tile wastes as pozzolanic admixture. *Waste Management*, *29*(5), 1666–1674. https://doi.org/10.1016/j.wasman.2008.10.019

Maxi Readymix Concrete, 2019
Maxi Readymix Concrete. (2019, March 20). *A History of concrete furniture and evaluation of current trends*. https://www.maxi.co.uk/concrete-furniture/

Medina et al., 2016
Medina, C., Sánchez De Rojas, M. I., Thomas, C., Polanco, J. A., & Frías, M. (2016). Durability of recycled concrete made with recycled ceramic sanitary ware aggregate. Inter-indicator relationships. *Construction and Building Materials*, *105*, 480–486. https://doi.org/10.1016/j.conbuildmat.2015.12.176

Mohit et al., 2023
Mohit, M., Haftbaradaran, H., & Riahi, H. T. (2023). Investigating the ternary cement containing Portland cement, ceramic waste powder, and limestone. *Construction and Building Materials*, *369*. https://doi.org/10.1016/j.conbuildmat.2023.130596

Mulyono, Thamrin & Antoni, 2017
Mulyono, G., Thamrin, D., & Antoni. (2017). Development of modular outdoor furniture product using lightweight concrete for public parks in Surabaya. *IOP Conference Series: Materials Science and Engineering*, *234*(1). https://doi.org/10.1088/1757-899X/234/1/012022

Ogawa et al., 2020
Ogawa, Y., Bui, P. T., Kawai, K., & Sato, R. (2020). Effects of porous ceramic roof tile waste aggregate on strength development and carbonation resistance of steam-cured fly ash concrete. *Construction and Building Materials*, *236*, 117462. https://doi.org/10.1016/j.conbuildmat.2019.117462

Özalp & Yilmaz, 2020
Özalp, F., & Yilmaz, H. D. (2020). Fresh and hardened properties of 3D high-strength printing concrete and its recent applications. *Iranian Journal of Sci-*

ence and Technology – Transactions of Civil Engineering, *44*, 319–330. https://doi.org/10.1007/s40996-020-00370-4

Peterson, 2002
Peterson, J. (2002). Concrete furniture market expanding rapidly. *Concrete Decor*, *2*(1).

Šál, & Dědič, 2020
Šál, J., & Dědič, M. (2020). Application of modeling processes and 3D print on casting molds for concrete furniture. *IOP Conference Series: Materials Science and Engineering*, *728*(1). https://doi.org/10.1088/1757-899X/728/1/012014

Scrivener et al., 2018
Scrivener, K., Avet, F., Maraghechi, H., Zunino, F., Ston, J., Hanpongpun, W., & Favier, A. (2018). Impacting factors and properties of limestone calcined clay cements (LC^3). *Green Materials*, 7(1), 3–14. https://doi.org/10.1680/jgrma.18.00029

Scrivener, John & Gartner, 2018
Scrivener, K. L., John, V. M., & Gartner, E. M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. *Cement and Concrete Research*, *114*, 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015

Sertoglu, 2021
Sertoglu, K. (2021, April 28). *Slicelab spearheads concrete furniture using 3D printing technology*. https://3dprintingindustry.com/news/slicelab-spearheads-concrete-furniture-using-3d-printing-technology-189243/

Seymour et al., 2022
Seymour, L. M., Keenan-Jones, D., Zanzi, G. L., Weaver, J. C., & Masic, A. (2022). Reactive ceramic aggregates in mortars from ancient water infrastructure serving Rome and Pompeii. *Cell Reports Physical Science*, *3*(9), 101024. https://doi.org/10.1016/j.xcrp.2022.101024

Siddique et al., 2019
Siddique, S., Chaudhary, S., Shrivastava, S., & Gupta, T. (2019). Sustainable utilisation of ceramic waste in concrete: Exposure to adverse conditions. *Journal of Cleaner Production*, *210*, 246–255. https://doi.org/10.1016/j.jclepro.2018.10.231

Università di Bologna, 2023
Università di Bologna. (2023, September 15). *Furniture Worldwide*. https://www.statista.com/outlook/cmo/furniture/worldwide#sales-channels

WBCSD, I.-I. E. A., 2009
WBCSD, I.-I. E. A. (2009). *Technology roadmap. Low-carbon transition in the cement industry*. www.wbcsdcement.org

THE NEXT STEPS OF THE OF THE SPOKE 1'S PROJECT. DIGITAL PLATFORM DESIGN FOR THE SUSTAINABLE TRANSFORMATION OF THE MADE IN ITALY MANUFACTURING INDUSTRY

Marion Josserand, Michele Zannoni*, Laura Succini**

Introduction

Digital technologies play a key role in knowledge sharing and networking and the role of these online tools is well-established and widely used both in the development of collective aggregation processes and in the dissemination of knowledge (Tapscott, & Williams, 2010).

Since the first decade of the Internet's development, collaborative processes have first developed in the format of forums and later then in the configuration of more aggregated communities in the virtual and online context (Rheingold, 1993). In the personal sphere these tools have taken the name of social networks; within the professional sphere they have evolved in sectoral ways depending on the goals on which they were born.

The need to build one's own tools for design is an innate element in humans and designers, and so collaboration tools are also part of it. For this reason, the Advanced Design Unit at the University of Bologna has developed a portfolio platform dedicated to Spoke 1 innovation projects to build a virtual and collaborative extension of MICS projects with the aim of developing an open system for collaboration among companies to serve and protect Made in Italy.

This paper presents the design process followed, as well as the resulting digital portfolio, its scope and objectives, organization and features.

The digital portfolio, a platform for Made in Italy innovation

**Department of Architecture, Alma Mater Studiorum - University of Bologna, Italy*

As part of the research activities of the MICS extended partnership, this portfolio aims to support the free flow of information and know-how for sustainable and circular innovation.

Initially conceived as a means of dissemination for the Spoke 1, it was then thought of as a strong instrument that could enhance collaborative opportunities for future sustainable manufacturing practices (Moghrabi et al., 2023). The aim of this digital portfolio platform is to develop collaborative processes and to enable projects and researchers to continue the virtuous process born from the collaboration between universities and companies.

This portfolio, conceived as a collaborative digital platform, aims to strengthen cross-sector synergies throughout Italy. By showcasing the know-how and skills of the players involved in the various projects, and offering networking functions, it aims to support innovative and sustainable collaborations.

To ensure the adoption of this digital platform, the ADU developed a research and development protocol based on interdisciplinary collaboration and co-design methodologies. After creating a group of experts from the various fields involved in the Spoke 1 projects, the ADU developed a user-centered design process during which all aspects of the future portfolio would be discussed.

1. Co-design process

The design process followed was primarily inspired by the principles of collective intelligence (Surowiecki, 2004). From the outset of the process, a group of researchers was formed, including a representative from each of the projects involved in Spoke 1. The researchers were equally represented in terms of gender, diverse in terms of field experience and expertise, and heterogeneous in their use of the already existing digital research platforms. This choice was made to guarantee a holistic approach to the challenges facing the portfolio, to ensure the development of a product suited to the diversity of its future users and therefore its usability and attractiveness.

The design process was developed using a back-and-forth methodology between desk and field research, case study and collaborative workshops with the group of experts.

The first stage of the design process involved studying forty-seven digital platforms, including research dissemination

and educational platforms, project portfolios, open data archives and community-focused platforms. This enabled the ADU project team to identify the main online trends in this context, the main users, as well as some interesting features and the organization of filterable content.

In parallel with this desk research, a series of individual interviews was conducted with project representatives to explore their different needs and expectations in terms of a common digital portfolio. At this stage of the process, interviews were conducted individually to explore each person's needs and expectations in depth, without interfering with and/or influencing the others.

The summary of the interviews enabled the ADU team to individualize a first portfolio identity that will be discussed and refined during a series of three workshops where all project representatives were brought together.

Workshop 1: Portfolio identity development

This workshop aimed to align the different representative on a common understanding of the digital portfolio and to specify its scope. A co-design session based on the interviews' synthesis, settled the digital portfolio identity and a collaborative brainstorming allowed the group to explore how to respond to the portfolio design principles.

- *Vision*: "A way of presenting aggregated and well-organized content that encourages collaboration among stakeholders";
- *Goals*: Consultation, Contribution, Social Link;
- *Missions*: To showcase projects, to aggregate and to organize heterogeneous content, to connect stakeholders, to protect and make MICS competitive;
- *Main users actions*: Discover, Show, Share;
- *Design principle*: 1. Make use easy and fast, 2. Create a guided hierarchy from group to individual, 3. Customize paths according to one's goals, 4. Give visibility to the intersectionality of projects, 5. Allow people to see and be seen, 6. Create social connection, online and in presence, 7. Supporting mutual aid, 8. Thinking levels to protect ourselves, 9. Having a benevolent gaze.

Workshop 2: User's journey exploration

The second workshop focused on the future user journey through the portfolio. A disruptive activity led the group to explore user needs, then a synthesis activity enabled the group to organize the portfolio's content, identify functionalities and begin the information architecture.

In this workshop, the main parts has been organized as well as the taxonomy:

- A portfolio section and a personal space for social networking and information management;
- Two main tabs: one to present the projects and the other to present the people involved in the projects;
- The Projects and People pages have been organized into content sections;
- Tags have been written and associated with each project to organize and filter them.

Workshop 3: Personal area features for network setup

This workshop enabled the group to delve deeper into the user journey, focusing more on the specific needs of each project in terms of project contribution and people collaboration. This time was devoted to projecting user needs in their personal area, imagining certain functionalities required to create networks, and designing the conditions of access to sensitive data. Some interesting point were individuated:

- All the functionalities to be integrated into the personal space have been defined (profile and project page management, notification parameters, project confidentiality, messages, etc.);
- The personal data required to access the portfolio has been determined;
- Chat and forum functions were selected for social exchange, as was the integration of professional e-mail;
- A "challenge" section was designed to set up future collaboration;
- Three types of access have been set up to ensure project confidentiality: Consultation, Access to sensitive data, Use of project tools and software.

This series of workshops enabled us to obtain a precise hierarchy of information relating to our multidisciplinary context. It also enabled us to think prospectively about the interaction with future users, necessary to maintain its attractiveness over time as a manufacturing innovation hub.

2. Scope and objectives of the portfolio

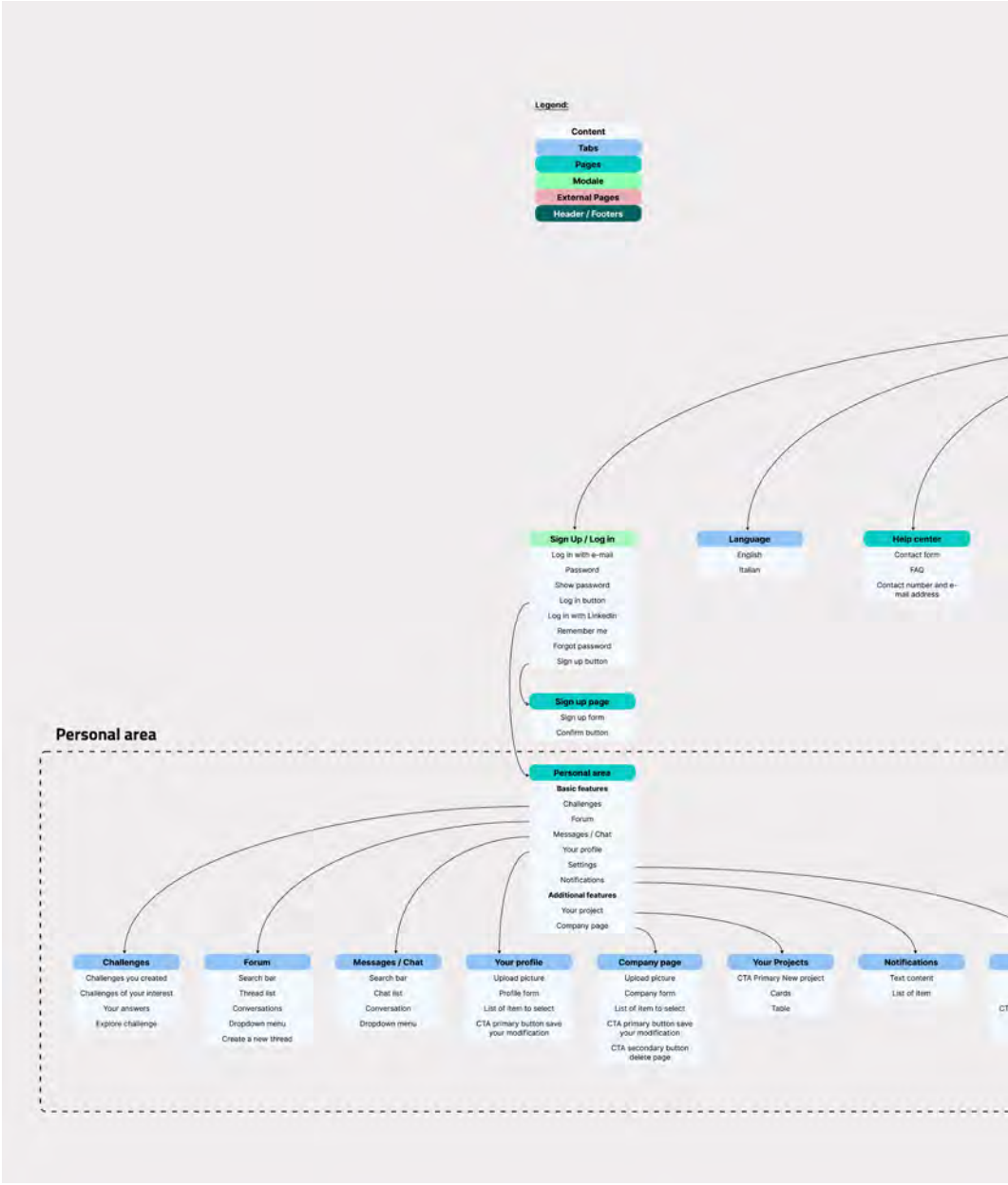
There are two main objectives: research dissemination and network building. As the portfolio serves as a centralized place to present the results of Spoke 1 projects, it also aims to create cross-sectoral links between the actors in these projects.

The creation of a single dissemination platform allows the different projects players to capitalize even more on recorded data and enable porosity of results across sectors. This reinforces the immediate effects of digitization on environmental and social sustainability. (Marrone & Raimo, 2021).

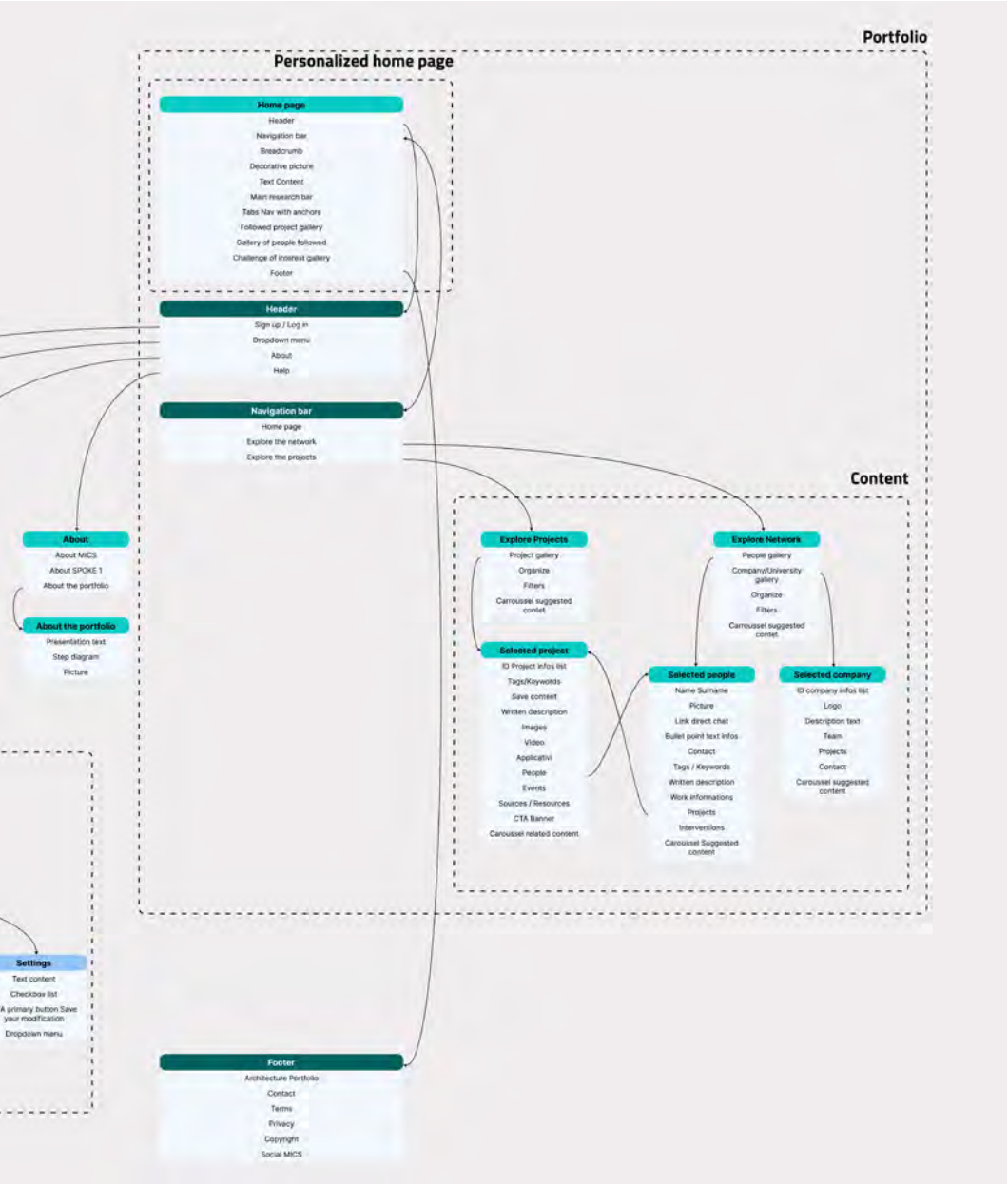
Initially, the portfolio will provide MICS stakeholders with data, articles, digital tools and software resulting from three years of research, promoting sustainable production processes, supporting the circular flow of materials and their manufacture across the territory, streamlining information exchange.

Secondly, because it will bring together a wide range of players, sectors and disciplines, it aims to engage these players in unprecedented collaboration and innovative research projects. By pooling the know-how and skills of players within a single platform, the portfolio's long-term ambition is to increase the sustainability of information flows over time and Made in Italy competitiveness.

The portfolio has been designed with an emphasis on both the circularity of knowledge and skills, and the protection of project results. In fact, it is accessible only with authorization, for local players who are interested and ready to contribute to new projects for Made in Italy. Certain levels of confidentiality have been designed to combat data leakage and reinforce open innovation within the Italian territory.



1. Platform information architecture.
All images are reproduced in color in the online edition of the book.


Portfolio
Personalized home page
Home page
Header
Navigation bar
Breadcrumb
Decorative picture
Text Content
Main research bar
Tabs Nav with anchors
Followed project gallery
Gallery of people followed
Challenge of interest gallery
Footer
Header
Sign up / Log in
Dropdown menu
About
Help
Navigation bar
Home page
Explore the network
Explore the projects
Content
About
About MICS
About SPOKE 1
About the portfolio
About the portfolio
Presentation text
Step diagram
Picture
Explore Projects
Project gallery
Organize
Filters
Carroussel suggested contet
Explore Network
People gallery
Company/University gallery
Organize
Filters
Carroussel suggested contet
Selected project
ID Project infos list
Tags/Keywords
Save content
Written description
Images
Video
Applicativi
People
Events
Sources / Resources
CTA Banner
Carousel related content
Selected people
Name Surname
Picture
Link direct chat
Bullet point text infos
Contact
Tags / Keywords
Written description
Work informations
Projects
Interventions
Carousel Suggested content
Selected company
ID company infos list
Logo
Description text
Team
Projects
Contact
Carousel suggested content
Settings
Text content
Checkbox list
A primary button Save your modification
Dropdown menu
Footer
Architecture Portfolio
Contact
Terms
Privacy
Copyright
Social MICS

3. Portfolio features and functionalities

The digital portfolio is divided into two parts: one presenting the projects and the people involved in them (the portfolio part), and the other dedicated to the functionalities required for future contribution and social exchange (the personal space).

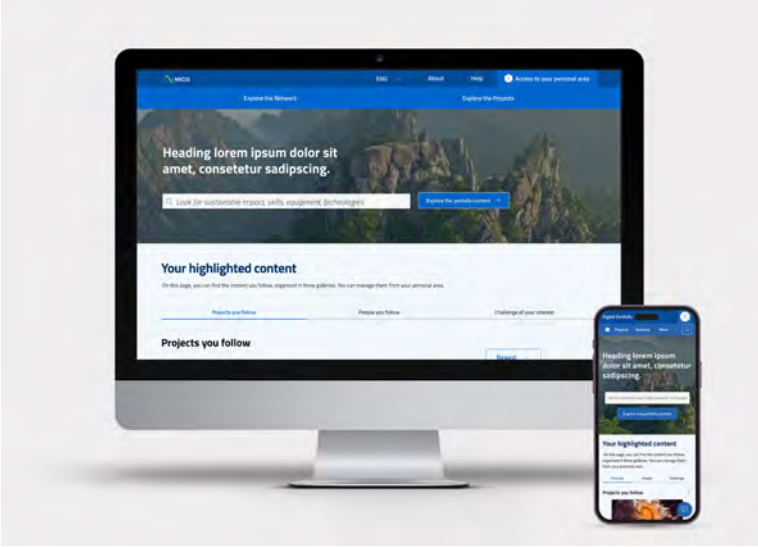
The portfolio section is divided into two overlapping sections: Network and Project.

Both can be filtered according to a strict taxonomy, co-designed within the team, which encompasses methodologies, materials, research field and project type. Each project uploaded to the platform and each stakeholder involved will have a dedicated page divided into sections. This boxed organization supports the user experience by making it easier to find information in a complex ecosystem. Once one's need answered, it is possible to navigate through the different content thanks to a tag system that create bond between then.

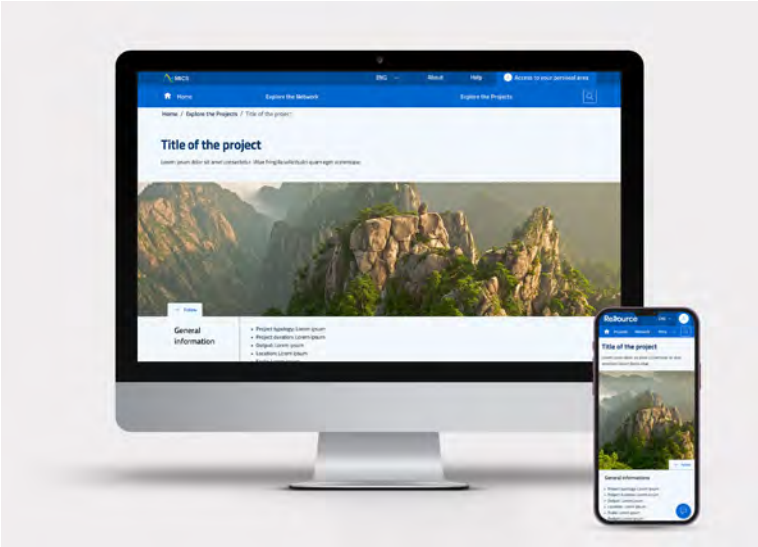
The people experience has been designed to be personalized, allowing users to save specific pages and content for quicker access, or to interact directly with them by sending messages, responding to challenges or proposing contributions to projects. This specific platform goal is necessary to develop the project's community of researchers and make it active and open to the Italian industrial system. In fact, a host of exchange functions between users of the platform will enable a continuous flow of innovation. A forum will enable users to discuss projects and research topics, chat will enable them to exchange directly with each other, and challenges are a feature designed to support innovation and new collaborations, by responding to the needs of other network players (fig. 1).

Finally, from the personal area, users can manage their pages and settings, content and access to project pages, create challenges, contribute to other people's projects, manage notifications, e-mail integration and settings.

The portfolio interfaces use the graphical charts of the design system Design. Italia,[1] designed and used for public services digital touchpoints. Thus, enabling us, to be recognized as an Italian Open Access platform for Italian industrial innovation. As much as possible it has also been thought to be accessible and sustainable. Thought as "mobile first design," the struc-



2. View of the home screen (home) of the computer and mobile platform.



3. View of the section dedicated to individual Spoke projects.

ture has been simplified. Thus, implying reducing the number of pages and superficial functionalities, carrousel, animations, decorative images e.g. (both aspects are deeply related between product carbon footprint and accessible experiences).

Once the content ready to be integrated, alternative texts will be written on images, videos, data representations, icons etc. to ensure the accessibility of the content. The format and resolution of the medias will be chosen to be accurate and sustainable (figs. 2-3).

4. Expectations and forecasts

As digital transformation increases international competition, maintaining Italy competitive in this sector will be one of the biggest sectors of the next years, mostly for the actors operating in manufacturing industries (Bryson et al., 2015).

That is why this digital project has been designed to enhance the value of experts and stakeholders working on sustainable and circular projects for Made in Italy. Conceived as an innovation hub for the Italian industrial market, it promotes opportunities for multi-partner collaboration and research, supporting the competitiveness, flexibility and sustainability of the Made in Italy market. Consequently, after an initial launch for Spoke 1 stakeholders, this portfolio aims to integrate other Italian players and local projects to strengthen innovation in the various sectors.

Designed to have a decentralized moderation, where people take care of their own projects and can invite external actors, the project can be rapidly extended to other sectors and disciplines in a very agile way. In addition, the protection of the content will play a key role on the network strengthening and attractiveness. Players will be invited to contribute to the network to access to specifics data, thus, reinforcing the common know-how.

To do so, creating a network lead by trust in between the actors will be determinants for knowledge sharing (Capestro et al., 2024), that is why the common responsibility of the stakeholders involved as well as the Open Access moderation will play a key role to set a transparent and trustworthy environment.

A positive synergy will gradually take root, thanks to a growing network nourished by the discoveries of previous projects. Like a virtuous circle, the strength of this portfolio will be to extend over time the field and problematics of the Italian market covered. Thus reinforcing the attractiveness of the network itself and settling a sort authority as a reference for Italian sustainable innovation.

Note

[1] https://designers.italia.it/.

References

Bryson et al., 2015
Bryson, J. M., Crosby, B. C., & Stone, M. M. (2015). Designing and implementing cross-sector collaborations: Needed and challenging. *Public Administration Review*, *75*(5), 647–663. https://doi.org/10.1111/puar.12432

Capestro et al., 2023
Capestro, M., Rizzo, C., Kliestik, T., Peluso, A. M., & Pino, G. (2023). Enabling digital technologies adoption in industrial districts: The key role of trust and knowledge sharing. *Technological Forecasting and Social Change*, *198*, 123003. https://doi.org/10.1016/j.techfore.2023.123003

Moghrabi et al., 2023
Moghrabi, I. A. R., Bhat, S. A., Szczuko, P., AlKhaled, R. A., & Dar, M. A. (2023). Digital transformation and its influence on sustainable manufacturing and business practices. *Sustainability*, *15*(4), 3010. https://doi.org/10.3390/su15043010

Marrone & Raimo, 2021
Marrone, A., & Raimo, N. (2021). *Sostenibilità e digitalizzazione, un approccio economico aziendale*. Giuffrè.

Rheingold, 1993
Rheingold, H. (1993). *The virtual community: Homesteading on the electronic frontier*. Addison-Wesley Pub. Co.

Surowiecki, 2004
Surowiecki, J. (2004). *The wisdom of crowds: Why the many are smarter than the few and how collective wisdom shapes business, economies, societies, and nations*. Doubleday & Co.

Tapscott, Williams, 2010
Tapscott, D., & Williams, A. D. (2010). *Wikinomics: How mass collaboration changes everything* (Expanded ed., paperback ed). Portfolio/Penguin.

Finito di stampare nel mese di giugno 2025
per i tipi di Bologna University Press

This book presents ten innovation fronts developed in parallel through research funded within Spoke 1 of the MICS (*Made in Italy Circolare e Sostenibile*) Partnership. Set within the framework of Digital Advanced Design, the project explores the role of design and digital innovation in promoting sustainable and circular transitions across various *Made in Italy* sectors, bringing together knowledge and expertise from academic, industrial, institutional, and professional fields.

Flaviano Celaschi
Full Professor in Advanced Design at the University of Bologna. Since 1995, he has worked on design processes and cultures in various Italian universities. He leads Spoke 1 of the project *Made in Italy Circolare e Sostenibile* and is Editor-in-Chief of *diid. Disegno industriale Industrial Design journal*. He is the author of over one hundred scientific publications in the field of design driven innovation.

Laura Succini
Researcher in *Responsible Advanced Design* at the University of Bologna. Her research focuses on sustainable design and collaborative approaches within territories, with particular attention to intangible dimensions of *Made in Italy*. Since 2023, she has also been investigating processes and methods for inhabiting extreme environments.

Michele Zannoni
Associate Professor in Industrial Design at the Università di Bologna. His published articles and books explore the intersection of interaction processes and visual and product design. His scientific research is focuses on digital, interaction and physical products and the evolution of the user interface.