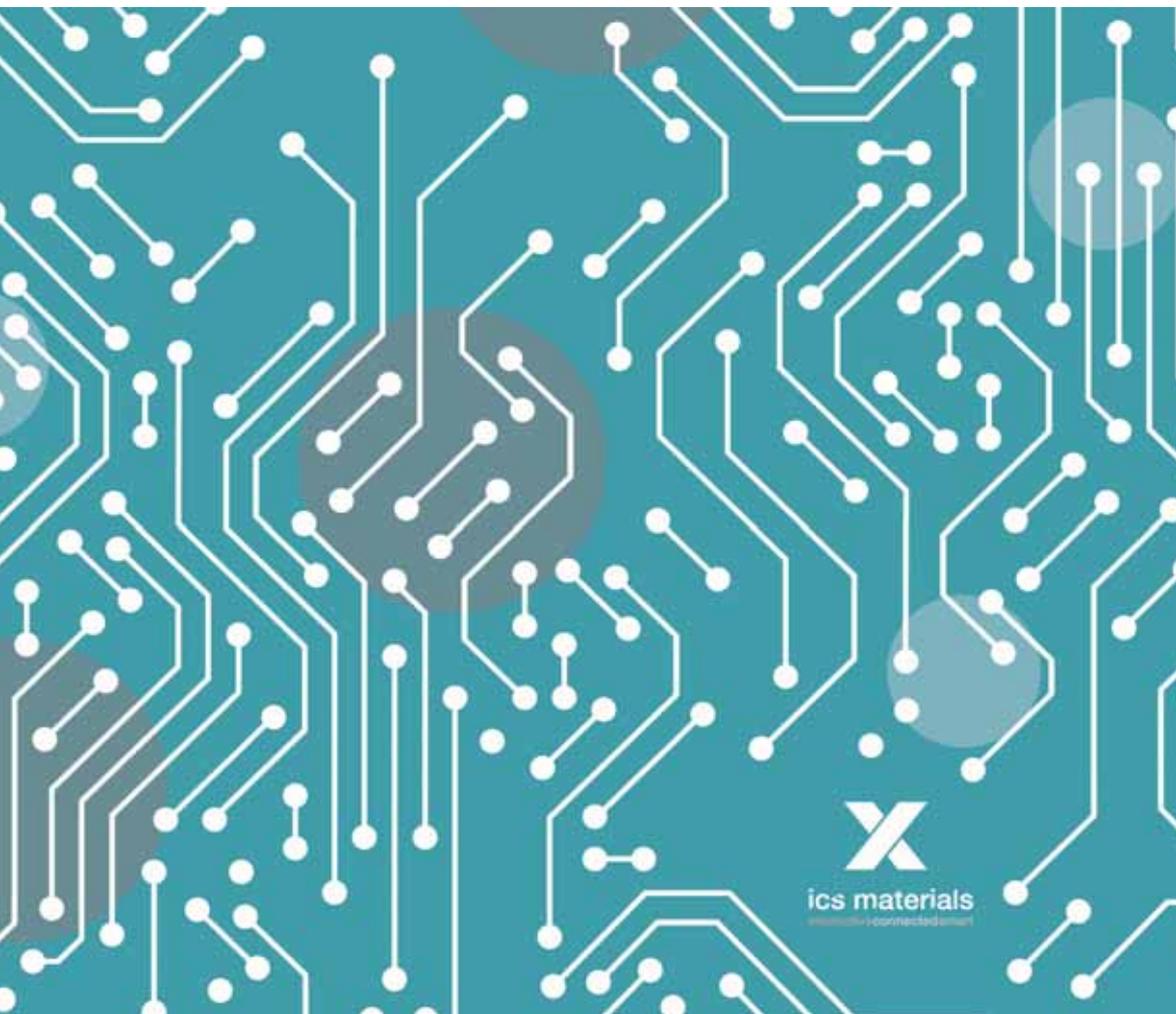


ICS MATERIALS

Interactive, connected, and smart materials



edited by Valentina Rognoli and Venere Ferraro



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D.I. **FRANCOANGELI** OPEN  ACCESS
DESIGN INTERNATIONAL

Editors of this book acknowledge funding received by FARB funds of the Design Department of the Politecnico di Milano.

Cover image: Helga Aversa.

ISBN e-book Open Access: 9788835115649

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ICS Materials' theoretical background

by *Valentina Rognoli, Venere Ferraro*

1. About ICS Materials Project

In the panorama of contemporary design, there are evident needs strongly conditioned by the technological system characterized by the ubiquity and connectivity of everyday artefacts that create material systems always more Intelligent, Connected and Smart. Designers are asked to imagine new material experiences in daily life, through communicating and interactive devices that will be future everyday objects (Giaccardi, 2015; Giaccardi, 2018; Chuang et al., 2018).

Even the multidisciplinary Human-Computer-Interaction (HCI) community, after having pushed the research towards the dematerialization of technologies, is re-evaluating the significance attributed to the sensory/perceptive involvement with physical matter, promoting the role of materials as a lens (“material lens”) through which looking at the future dynamics of interaction, by recognizing the value of tangible side (Wiber, 2014;).

In the last few years, new classes of advanced smart materials are emerging, expanding the available domain of materials for design and applications. This evolution is encouraged by a growing technological development that feeds miniaturization of components, such as sensors, microprocessors, and actuators, and allows operating on a micro-and nanoscale (Valgarda et al., 2010; Razaque et al., 2013). Also, it fuels a continuous democratization process that fosters knowledge sharing, open-source technologies and trans-disciplinary collaborations between design, material science, computer engineering and life sciences, to some extent.

The materials emerging from this conjunction of factors are overpassing conventional smart materials by showing higher degrees of intelligence, thanks to the seamless integration of embedded and seamless technologies that allows them to sense, process and respond to external inputs, and being

programmable and re-programmable (Andreoletti and Rzezonka, 2016; Tibbits and Cheung, 2012; Tibbits, 2017; Scott, 2018).

We call this novel class of materials as **ICS Materials**, an acronym for **Interactive, Connected and Smart Materials** (Rognoli et al., 2017; Ferrara et al., 2018, Parisi et al., 2018 (a); Parisi et al., 2018 (b); Parisi et al., 2020). The concept of ICS Materials leverages the meaning of Material Experience (Karana et al., 2014; Karana and Giaccardi, 2015) that consider the material as “*being simultaneously technical and experiential*” expanding it to the multidisciplinary context of HCI.

This book aims to disseminate a research project focused on ICS (Interactive, Connected, Smart) Materials and the results of the research concerning this particular typology of design materials. The study, funded by FARB (Fondo di Ateneo per la Ricerca di Base), Politecnico di Milano, and carried out by a multidisciplinary team of researchers of the Department of Design, is situated in the intersection of design, new materials, and interaction, to define and support the theoretical and practical development of such a cutting-edge research area.

The questions the research intended to answer are: how will the everyday objects be in the future? Will they still use the contemporary conventional materials? Will they always have the functional characteristics and the performances sufficient to meet new needs? What will be the material experiences emerging in this context, and how will they evolve in perspective? Are there any methodologies that can facilitate the design process towards meaningful material experiences in the field of design?

With such premises, the research on ICS Materials proposed an adaptation of the traditional methods, skills and knowledge already developed in the field of materials for design. It favours the progressive transition towards an increasingly interactive, connected and smart dimension of design products and services (Wiberg and Robles, 2010; Hummels and Frens, 2008; Zimmerman et al., 2007; Frens, 2006), which unfolds in the IoT, Internet of Things (Kuniavsky, 2010).

The definition of ICS Materials encompasses material systems that are:

- Able to establish a two-way exchange of information with human or non-human entities.
- Linked to another entity or an external source, not only through the internet and digital network.
- Able to respond contextually and reversibly to external stimuli by changing their properties and qualities.
- Programmable, not only through software.

They can do that through the combination of electronic, chemical, mechanical, and biological means. By using integrated and seamless technologies, such materials can be used as reprogrammable material interfaces for many sectors (transportation, consumer electronics, wearables, smart objects, architecture, cultural heritage, etc.), showing enormous potential in terms of customization, sustainability and reduction of resources, and complying with the Internet of Things, Artificial Intelligence and Industry 4.0.

Throughout a bottom-up approach, labs and companies around the world are developing samples, demonstrators and prototypes of such materials. There is the necessity to set a boundary and frame the complexity of such phenomenon and critically reflect on their sustainable development, their innovative potentials, and their integration into the industrial framework, the social context, and the design space.

The research here presented contributes to building the foundation of an emerging area of research promising to make research groups and departments more competitive at a national and international level. More investigations require to be addressed for identifying innovative guidelines, scenarios, and methods facilitating the development and integration of advanced hybrid materials systems, considering creativity, manufacturing, sustainability, and application issues.

These innovative tools to approach such emerging materials are a competitive factor in the field of **research, education, and industry**; in anticipating and facilitating their industrial development, market deployment and spread in the user's everyday environment, having a social and technological impact.

The results of this research, i.e., knowledge, models, tools, guidelines, scenarios, and method, are expected to benefit and contribute to the transition towards a more resilient, adaptive and connected future. The book means to be a valuable resource for **academic researchers, educators, industrial managers, designers, engineers, interaction designers and materials experts**, who want to discover more about new materials and technologies and need knowledge and tools for their development and teaching.

The research project was divided into four main stages informed and inspired by the *Double Diamond Process Model*, i.e., Discover, Define, Develop and Disseminate¹ (Hunter, 2015).

Following such phases, the results of the research could be framed as follow:

- State of the Art about the topic, mapping literature, theoretical concepts and models, existing best examples and the actors that are involved in the phenomenon.

¹ <https://www.designcouncil.org.uk/news-opinion/double-diamond-universally-accepted-depiction-design-process>

- The exploration of the grounding and border disciplines and concepts concerning the new topic of research, thanks to the contribution of international guest experts from education and practice in the fields of Design, New Materials, and Interaction.
- Proposes innovative guidelines, techniques and scenarios for the ideation, development and multi-sectors application.
- Proposes and applies a new method to ideate the design of such materials for intended application contexts, tested in an innovative format of design education workshop for multidisciplinary students.

2. Contents

The book is shaped into three main sections by giving a general overview of the research's findings.

In the first part, external guest authors are called to contribute by bringing their research topics as grounding or border notions to the research project. Some of the authors already presented their contents during a series of open lectures organized by the research team in 2017-2018, such as:

- **Gaia Crippa**, Senior CMF Designer and Materials Specialist at Chris Lefteri Design, London, UK: The new material experience. Interactive, connected and smart materials.
- **Daniela Petrelli**, PhD, Professor of Interaction Design at the Art & Design, Research Centre, Sheffield Hallam University, UK: Arguing the case for holistic design. Unpacking the relationship between materials and interactive experience.
- **Barbara Pollini**, PhD Student at Polimi and Sustainable designer and professor in Materials and new technologies for the project innovation at Naba Design University, Milan, Italy: Sustainable design and biomaterials. Exploring interactivity, connectivity and smartness in nature.
- **Marta González Colominas**, PhD, Coordinator of the Materials and Sustainability area for the Degree in Engineering in Industrial Design at ELISAVA, Barcelona, Spain: Smart materials driven design. Design to achieve dynamic experiences.
- **Oscar Tomico**, PhD, Head of Studies of the Degree in Engineering in Industrial Design at ELISAVA, Barcelona, Spain: Designing for soft interaction. Designing products that are worn (everyday).
- **Vasiliki Tsaknaki**, PhD, interaction designer and crafter, teaching at KTH Royal Institute of Technology at the department of Media Techno-

logy and Interaction Design: Exploring materials and making processes of computational artefacts, through studio craft practices.

- **Manuela Celi**, PhD, Associate Professor at the Design Department, Politecnico di Milano, Italy: Exploring the futures. How design shapes next directions.
- **Seetal Solanki**, Founder and Creative Director of Ma-tt-er, London, UK: How materials matter. The past, present and future of ICS Materials.
- **Manuel Kretzer**, PhD, Professor for Material and Technology in Design, Dessau Department of Design, Anhalt University of Applied Sciences, Cologne, North Rhine-Westphalia, Germany. Founder of Materiability. Partner at Responsive Design Studio: Materiability. Educating smart materials for design and architecture.
- **Maurizio Montalti**, Designer / Researcher / Educator / Entrepreneur | Founder&Director @Officina Corpuscoli | Co-founder & Director @mogu: Growing design & growing materials. The everyday practice, its outcomes and opportunities and the related implications.

Seven chapters constitute the first section of this book and will guide the reader into the understanding of the vast panorama that examines the intersection between materials, technology and digitization.

In the first chapter, a case study developed inside Elisava will show how engaging interaction through smart materials and a sensory language by using *Smart Material Driven Design Method*. While, in the second one, experimental case studies using interdisciplinary processes deploy the increasing overlapping of the *digital with the real/hybrid materials* proving that there are no classical categories to associate to the materials anymore.

Further, the book will give a hint on the topic of *sustainability*. It does it through two more chapters respectively dedicated to bioplastic and robotic fabrication describing customized methods of fabrication, parametric design modelling and the potentials of do it yourself (DIY) bioplastic in combination with cutting edge robotic fabrication. Case studies on *biomimicry*, *bio fabrication*, *biomaterials*, *biodesign* by using co-participated design activities with living organisms, will be presented.

Besides, three case studies related to *digital craftsmanship*, practices that combine physical with computational materials will be described by highlighting future scenarios such as sustainable practice and the value of craft, the sensorial and the impermanent aspects of craft materials, and program smart materials.

After that, there is a chapter focused on Light. Touch. Matters (LTM) project², a collaboration between designers and materials scientists aimed at

² <https://www.tudelft.nl/en/ide/research/research-labs/emerging-materials-lab/lighttouch-matters/>

providing insight related to underdeveloped smart materials composites, and how to facilitate communication between designer and materials scientists and the importance of experience prototyping.

Finally, the first section concludes with a chapter that will instead exploit the meaning, opportunity and potentiality to really know materials through materials libraries: an example of how organizing an ICS Material collection in functional groups (composites and wearable) will be provided.

The second section of the book will present the State of the Art and the map of the *ICS Materials phenomenon*. In the first chapter, the definition of the phenomenon of ICS Materials as the main output of the research, is described and contextualized. In this chapter, **the notion of Materials Experience** is explained and used as a lens to interpret ICS Materials. The experiential patterns that ICS Materials enable and imply are presented and discussed.

In the second and the last one, a *map of materials and a map of practices* are presented. The main sub-classifications of ICS Materials according to their complexity degree and behaviours, are here provided.

In the third section of the book, the researchers taking part into the research project focused on anticipating scenarios for the development and integration of ICS Materials in their research areas, addressing the multidisciplinary dimension and impact of the project. Different sectors of application will be addressed, such as: Material surfaces industry; Exhibition and Smart Environments; Transportation, in particular, the Nautical sector; smart objects, in particular, advanced home appliances; Wearable Technologies. For each area, state of the art, case studies from research and education activities and future scenarios will be presented. This, to set the potentials and limits of the application of ICS Materials in that specific industrial area and design space. In this part, the participants to the project used the meaning and classification of ICS materials, considered as the main result of the project itself and they utilise it in different fields of application and design workshops with students with diverse backgrounds, including engineering, design and architecture.

The first chapter of this part describes five scenarios of visions developed during the workshop Ultrasurfaces. The meaning of the term ultrasurface as a sensorial interaction with the surface (today's relationship between physical and digital) will be given, the added value of the electronics augmentation, merging physical matter with data worlds without the need of keyboards, buttons or touchscreens, multisensory stimulation will be provided.

Afterwards, four chapters will go through the use of ICS Materials in (i) exhibition, (ii) smart products, (iii) wearables and (iv) yacht design:

- The use of technologies in museums, smart materials in the exhibit design field (3 dimensions: exhibition space, the cultural assets, the visitors) will point out the need of interaction both at the micro and macro level and the conception of the exhibition space as an ever-changing organism.
- The chapter will give an overview of the concept of smartness (smart qualities), smart product (3 categories), limits and opportunities of ICS materials for intelligent products, the most formidable challenge of standardization of smart materials and exciting opportunities in extra small and extra-large scales of applications.
- The description of a new class of electronic devices: stretchable electronics, will be highlighted. The need for lighter and more flexible materials for wearable design will be explained through the connection between wearable technologies and ICS Materials.
- The trend of full sensory experience in yacht design (part of the luxury design), a new practice of interaction between the yacht, the sea, and human behaviour, will be framed. In this case, the results of 5 workshops “Design for NautICS Materials” related to the use of ICS Materials for yacht design are presented..

At the end of the book, a survey on Materials Design methods and tools is presented to depict their limits and potentials, to introduce the ‘*Design for ICS Materials*’ approach. The methodology and its supporting tools and activities are here described.

3. Final Remark

The international scientific community agrees that materials are a key element for designing products, interfaces, furniture etc. Indeed materials are, on the one hand, the shape of which every artefact is made up of and, on the other one, a medium between the user and the surrounded by creating innovation that encompasses new languages, meanings and experiences (Karana et al., 2014).

Nowadays, emerging technologies are changing the way the human being lives, thinks, communicates and interacts with each other by imposing researchers, designers and practitioners to investigate the new way the materials will be studied, shaped and consequently experienced.

The rapid spreading and development of Internet of Things (IoT) smart products and interfaces, the responsive environment is adding new dimensions to humans everyday life: smartness, connectivity and interactivity.

This book centres the attention on the way materials are evolving by embracing these three layers focusing on a new class of Materials named ICS Materials.

Authors and contributors of this book explore the role of this new class of materials in the world of always evolving artefacts by reasoning on their unique performance, aesthetic and meaning, sensorial experience and mostly on the latest methods and tools to be used by designers in order to design with and for ICS Materials.

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Part One **Exploring grounding and border concepts**

1. Designing with Smart Materials. Talking Products

by *Marta González Colominas, Martin Andreas Koch,
Carlos Salas Muñozcano and Laura Clèries*
Elisava Barcelona School of Design and Engineering

1. Talk to Me! Design Needs Communication

In design, communication is fundamental to create a product that addresses a certain market or target. Particularly, in industrial design, the design dictates the understanding of and the communication with the object which will guide a correct use of the object and hence, will result in a high grade of functionality and user satisfaction (Aakhus, 2007).

As social animals, humans need communication to survive, to inform, provoke actions, create understanding and transmit ideas (Tomasello, 2014). Mainly, the transmitted information can be divided into two types: sensory and cognitive. Sensory information is assimilated by our brain naturally and color, shape, smell, touch and sound allow us to gain information about our environment rapidly. Cognitive information, in addition, is information that uses a code that has to be deciphered to be understood (Fan, 2014).

When designing meaningful objects, the object can interact and communicate with the user via cognitive information, displaying an alphanumeric message (traditionally through screens or displays), which the user can decode to understand the meaning (Colombo, 2016). Even though this is a straightforward approach, by incorporation of non-digital information into the environment of a user, we can create an intuitive and unobtrusive design that “speaks” to the user without needing continuous attention. This approach to a “calm and ambient technology” has already found its way into the world of computing (McEwen and Hakim, 2014). Ambient interfaces for peripheral interaction with computers have been developed (Hausen et al., 2012) and studies have shown that the created “Smart Surroundings” have the potential to transmit information more effectively, help to promote interpersonal communication (Karana and Kandachar, 2006) and change human behaviour based on information from the periphery (Forlizzi et al., 2007).

Additionally, the recent increase in digital technology and information overload has led towards the adoption of “digital detox” (or “data-detox”). By avoiding the plethora of digital information and spending time away from digital devices, stress can be reduced and quality of life improved (Morrison et al., 2014).

2. From Digital to Sensorial - Communication via Smart Materials Makes Sense

Based on the need for meaningful objects and the “digital detox” movement, it is worth exploring alternative ways to communicate information to the user (Rampino, 2018; Colombo and Rampino, 2013). To overcome the “digital feel” of an interface, the use of dynamic Smart Materials has been proposed for a more analogical and continuous interactions (Nijholt et al., 2012).

Dynamic interfaces have the potential to create meaningful and engaging interactions, and, as a consequence, user attachment to the product (Orth et al., 2018). The user experience can be enhanced by using sensory features (visual, auditory, tactile, olfactory and taste) that change in a proactive and reversible way over time, activating one or more of a user’s sensory inputs (Colombo, 2016).

Smart materials are to be considered the best candidates to provide dynamic experiences due to their ability to react to the environment and produce a change in colour, shape, etc. (González, 2018). Their dynamic properties can be used to redefine and augment Human Computer Interaction (Minuto et al., 2012) and create rich and emotional communication by means of analogical interaction, an aspect that conventional digital systems are lacking (Wakita et al., 2009). One example of smart materials for a meaningful sensorial communication is the product entitled *Measuring less to feel more*, designed by Mickael Boulay, which allows people with diabetes type 2 to measure their blood sugar levels by a changing colour-position correlation. A higher position of the colour indicator corresponds to a higher blood sugar level (Colombo, 2016).

As vision is our dominant sense (San Roque et al., 2015), visual stimuli such as colour, design, graphics and lighting play an important role when designing dynamic experiences (Hultén, 2017). The here presented methodology of designing with smart materials to create meaningful interactions will be focused on materials that change their visual appearance, even though this methodology can be transferred to other senses.

Chromoactive materials change their colour according to an external stimulus and have potentially the widest range of applications (Figure 1). Colour is capable of transmitting information and emotions and hence we can create codes that are simple to understand. (Duarte et al., 2017; Annamary, 2016). An example is the traffic light, in which we use red, yellow and green to indicate that we have to stop, that we have to proceed with caution or that we can go. These codes are easier to understand than a sign that literally says “stop”, “proceed with care” or “go”.

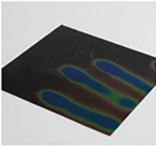
Thermochromic		Photochromic	Hydrochromic
Leuco dye	Liquid crystal		
 1	 5	 9	 13
 2	 6	 10	 14
 3	 7	 11	 15
 4	 8	 12	 16
1- Thermochromic Rub & Reveal Plastic Film with Adhesive Backing. 2- 3D Printing PLA Thermochromic filament. 3- Eclipse Thermochromic paint. 4- Thermochromic Polyester yarn. 5- SFXC © Cholesteric Liquid Crystal Ink. 6- SFXC © Liquid Crystal Ink - Sprayable. 7- Liquid Crystal Thermochromic Colour Changing Sheet. 8- Liquid Crystal Vinyl Sheet Colour Changing Matt Film. 9- Solar Zone. Photochromic inks and resins. 10- 3D Printing PLA Photochromic filament.		11- Reversacol UV activated photochromic ink. 12- SFXC © Photochromic Adhesive Backed Plastic Film sheet. 13- SFXC © Hydrochromic sprayable coating Ink. 14- White Hydrochromic ink aqueous base for screen printing. 15- Hydrochromic Reversible Wet and Reveal Screen Printing ink for fabric. 16- Hydrochromic Adhesive Backed Film Sheet White to Translucent.	

Fig. 1 - Visual table of chromoactive smart materials: thermochromic (leuco dyes and liquid crystal), photochromic and hydrochromic

3. How to Design Meaningful Objects with Smart Materials

For the design process, the used methodology is based on Smart Material Driven Design (Karana et al., 2015; González, 2018). According to this method, three main steps are involved. The first step is to take one particular material as a starting point. In step two, a material experience is designed for this material. As last step, the material is subjected to hands-on experimentation, which results in finding a practical use for the material.

In the here presented methodology, the first step is the selection of a family of materials (in this case, chromoactive materials). The second step is directed at the context and an objective, followed by the hands-on experimentation. The objective revolves around the transformation of digital information into sensorial information to design products that create a visual engaging experience through a colour change. Four key questions have to be addressed to decide on the chromoactive material and the desired functionality:

- A. What is the Context?
- B. What is the Objective?
- C. What Type of information can be used?
- D. What is the Origin of information?

A. Context

The context of the object is highly important for the design itself. It gives a framework for the object, which defines why, where, how, for what purpose and by whom the object is used. Taking into account the context in the early stages of design, allows the designer to increase the meaning of the object and create user satisfaction and attachment.

B. Objective

Knowing the object's context, the objective of the "talking" meaningful product has to be defined. In the presented methodology, we use four main levels of objectives:

- inform (data visualization); By displaying information, the smart material can visualize data, e.g. that it is a sunny day.
- generate an action; By transmitting information to the user, the object can provoke a reaction, e.g. instructing the user to apply sun lotion at a certain level of UV exposure.

- arrive at an understanding; The smart material can be used to not only provoke action, but also to understand the reason behind it, e.g. by making the user aware that UV exposure is not desirable and can lead to sun burns and even skin cancer.
- Transmit an idea; Going even further, depending on the implementation of the smart material, it can generate an idea, which goes beyond the previous levels, e.g. making the user aware of UV exposure and generating the idea to protect himself and others.

C. Type of information

Once the context and objective of the object is determined, it has to be decided which type of information will be transmitted. Information can be sensory or cognitive. While the sensory information can be visual, auditory, olfactory, tactile, vestibular or gustatory, cognitive information is predominantly transmitted by verbal or written communication via symbols, letters, pictograms, lexemes, grammar, sounds and phrases.

The right selection of the information type for the given objective is crucial, as the sensory information can be understood faster and more easily than its cognitive counterpart.

D. Origin of information

The origin of the information to be transmitted might be inherent to the object (or product) or it may be coming from an external source, being represented by the product. Intrinsic information refers to the product's features, inherited directly from its material and fabrication and consists in the personality, mode-of-use or origin of the product. The intrinsic information of an object is static and does not change significantly over time. Extrinsic information, in contrary, is information that originates from surrounding situations or phenomena, varies over time and changes the product dynamically. (Colombo, 2016)

In the design of objects with smart materials, the intrinsic and extrinsic information are brought together into one product. The intrinsic personality of the product comes from the conventional static material, while the dynamic information of external changes is implemented with smart materials.

Use Cases for Smart Materials

In this section, applications for colour coding dynamic materials are presented. In particular, hydrochromics, photochromics and thermochromics (leuco dyes and liquid crystal), that respond to humidity, light and temperature respectively, are going to be used to create an interactive dynamic object (González, 2018). This collection of Use Cases, has been designed by students from ELISAVA, Barcelona School of Design and Engineering. Of the four projects, two (Cosmos and Thermofretboard) have been developed during the second year of the degree in Engineering in Industrial Design, while two have been carried out during the fourth year (Hūxī and Talking Surface).

Hūxī

Hūxī is a redesign of personal protection air pollution masks. It explores how the technology of knitting with thermochromic yarns can generate communicative surfaces. Hūxī proposes a new methodology of interaction between the user and the environment, emphasizing two lines of communication: dynamism and personalization. Thanks to the application of thermochromic yarns in the pattern of the fabric, the mask communicates to the user that it is functioning. By changing colour from blue to white with every breath, the mask makes the intangible concept of air pollution visible. The mask is highly customizable, taking into account the differences of breathing patterns, either only nose, mouth or combining both, of the individual.



Fig. 2 - Hūxī

Context:

Air pollution is a current problem and has a significant impact on individuals, particularly in urban areas, where millions of citizens are exposed to levels above air quality guideline limits. The exposure to air pollution can lead to cardiovascular and respiratory diseases and it is the most significant environmental cause of premature death in the EU. (Doğan Öztürk et al., 2018). In this context, the Hūxī anti-pollution mask is targeted at health-conscious users that are active in urban areas.

Objective:

The objectives are to:

- inform; Visualization of the user's breathing to make the invisible tangible.
- generate an action; Create an attachment to the product of the user by means of style and fashion.
- arrive at an understanding; By the use of the mask, the user is compelled to experience the healthier, filtered air in comparison to the polluted un-filtered air.
- transmit an idea; By communicating its use, the mask searches to raise awareness of the air pollution in the population of urban areas. A colour change from blue to white aims to transmit purity and cleanliness.

Type of information:

The information transmitted is sensorial:

- visual; Breathing is made visible by the change of colour on a textile surface. The material displays shapes that change from blue to white in the mouth and/or nose area.

Origin of information:

- Intrinsic: The mask is made by knitting, which provides a breathable material, acting as a filter and prevents the mask from looking clinical or sterile, which makes it more likable for a daily use. The character of the material and the form of the mask provides all the information for its use.
- Extrinsic: The external phenomena that provokes the change in the dynamic material is the heat of exhaled breath. A thermochromic thread, knitted into the mask, changes its colour depending on the user's breathing pattern.

Thermofretboard

Thermofretboard provides a didactic dynamic surface by means of a laser-cut thermochromic liquid crystal sticker, with the shape of the Fender Stratocaster neck, one of the most iconic guitars in history. Liquid crystals are organic compounds with twisted helical molecular structures, which expand and contract, changing in the order of black to red, yellow, green and blue, when activated between 25°C and 30°C. Thermofretboard helps to visualize the fingering by means of the traces of colours and simplifies learning for guitar beginners by replacing the sheet music with colour visualization.

Context:

Humans are musical in nature. Flutes made of bones and mammoth ivory are the oldest discovered musical instruments in the world and date back over 40,000 years. Playing musical instruments has been linked to developing a better motor task competency, sharpens cognitive function, enhances social skills and can reduce the likelihood of dementia and cognitive impairment (Román-Caballero et al., 2018). Given the benefits of learning musical instruments, this project aims to increase the attachment of playing a guitar and making teaching and learning the instrument easier.

Objective:

The objectives are to:

- inform; Visualization of the position of the player's fingers over the fretboard in time.



Fig. 3 - Thermofretboard

- generate an action; Create an attachment to playing a guitar by the added value of visualization.
- arrive at an understanding; Make a third person understand how a guitar is played by showing the pathway of the player's fingers over the fretboard.
- transmit an idea; Generate an educative dialogue between the guitarist and the viewer.

Type of information:

- The information transmitted to the guitar player and the user is sensorial: visual; The position of the fingers on the fretboard is accompanied by a change of colour on the fretboard.

Origin of information:

- Intrinsic: The fretboard provides a smooth, "plastic" feeling surface. The lack of roughness promotes the touching of the surface and provides pleasant playing experience.
- Extrinsic: The external phenomenon in this case is the heat of the fingers that causes a colour change on the fretboard. To accomplish this, a thermochromic adhesive film is used as a reactive surface.

Cosmos

Cosmos is a self-watering planter for hydroponics that incorporates a hydrochromic water level indicator on the surface of the planter itself. Self-watering planters have a reservoir in the bottom of the planter that allows to add water for the plant. The hydrochromic paint on the outside of the red, porous clay is white when dry and translucent when wet. This reversible effect indicates the water level and lets the user know when and how much to water the indoor house plant. This approach allows to communicate in a very visual and clear way the water level of the plant.

Context:

Indoor house plants can be used to purify air and have additional health benefits (Kim et al., 2014). The interaction with indoor plants has been shown to reduce psychological and physiological stress (Lee et al., 2015). While the interaction is beneficial, the maintenance of plants can be difficult. Either too much or the lack of water can result in a sick or dying plant. The objective of this project is to facilitate the maintenance and interaction with the plant by providing an indicator for the watering of the plant.



Fig. 4 - Cosmos

Objective:

The objectives are to:

- inform; Visualization of the water level in the planter.
- generate an action; By creating a clear indicator for the water level, the user is enticed to water the plant, if need be.

Type of information:

- The information transmitted to the user is sensorial: visual; The water level in the planter is shown by a change of colour on the surface of the planter.

Origin of information:

- Intrinsic: The intrinsic information transmitted to the user by the material and fabrication of the planter does not differ from a conventional planter. The red porous clay surface evokes a homely feel.
- Extrinsic: The humidity of the planter's clay serves as dynamic external phenomenon. Depending on the level of humidity, the colour of the planter changes. This can be achieved by hydrochromic materials.

Talking Surface

Talking Surface is a project developed for the Spanish company Cosentino Group that uses UV-LEDs embedded in a material to change colour via photochromic dyes. In a shower, a pattern that represents “water” begins to appear on the wall and extends throughout the surface when a certain level of water consumption is reached. The pattern is blue in its lower part and red in its upper part. As red transmits uneasiness, the change in colour reduces the

user's stay in the shower by decreasing the level of comfort. This is achieved by measuring the water flow and activating the corresponding LEDs.

Context:

Talking Surface revolves around a shower tray, which is located in a private bathroom. According to an estimation of the Office of Community and Economic Development, 35-40% of household water is used for personal hygiene (shower and bath). This deliberate use of fresh water will result by 2030 in a 40% global water deficit (Connor, 2015). Even though the annual water consumption can be reduced to up to 50% by the installation of water efficient alternatives (Kelly, 2013), raising awareness in the consumer can reduce the impact of household water consumption even more.

Objectives:

The objectives are to:

- inform; Inform the user of the current water consumption during the daily shower routine.
- generate action; Encourage the user to reduce the consumption of water in the shower.
- transmit an idea; The red colour transmits the idea of uneasiness, so the person leaves the shower early (perception of time).

Type of information:

The information transmitted is sensorial:

- isual; The information provided to the user is a change of colour from blue to red; The direction of the colour change is upwards to indicate an increase in quantity.

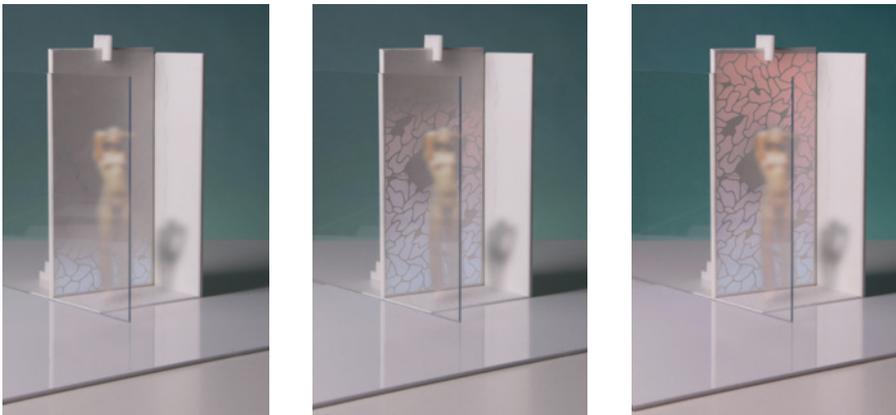


Fig. 5 - Talking Surface

Origin of information:

- Intrinsic: The surface of the walls indicates the presence of an indicator. The materials used for the shower are common materials that are welcoming to the user.
- Extrinsic: Water consumption over time affects the colour and position of a pattern on the shower wall. The gradual change of the photochromic material is provoked by UV-LEDs that are lit up in the interior of the material.

4. Concluding - What did the projects tell us?

The presented projects (Tab.1) have shown us that a problem-oriented methodology of designing with smart materials, using a more sensory and less cognitive language as an advanced way of communication, can counteract the increasing amount of digital information and potentially reduce information overload. The direct experimentation in workshops, together with the introduction of the chromoactive smart material selection, has allowed students to acquire the skills of designing and selecting materials, bearing in mind the dynamic properties and the objective, while treating both properties synergically.

By introducing a new concept, “Talking materials”, a dialogue between product and user can be generated. In the shown 4 cases, none used a digital alphanumeric display. Here, the change in the sensorial properties of the material generated the dialogue with the user. While three of the projects used the reactive material as sensor and actuator, one project, “Talking Surface”, added a layer of complexity by using the smart material as a display for an electronic device. This shows the potential for using dynamic materials for connected and smart applications.

In all 4 examples, the materials were not used just for their aesthetic character but also for their functionality. The smart materials add an extra layer of information, simplified and implicit, but potentially more engaging, that speaks to the user and gives the impression of the object being alive.

Thanks to Raquel Tresserra (Anti-pollution mask Hūxī), Daniel Riba (Thermofretboard), Sonia Cárabe, Berta Colomer, Marta López, Laura Monforte (Cosmos) and Carlos Salas (Talking Surface), for allowing the use of images of their projects.

Tab. 1 - Application for Smart Materials

	Applications for smart materials			
	<i>Hūxī</i>	<i>Thermofretboard</i>	<i>Cosmos</i>	<i>Talking Surface</i>
Context	Air pollution	Musical practice	Indoor planting	Private shower
Objective	Personal protection, raise awareness	Visualization, attachment, education	Communication with plants	Reduce water consumption
Type of Information	Sensorial (visual)	Sensorial (visual)	Sensorial (visual)	Sensorial (visual)
Type of chromoactive	Thermochromic (lyco dye)	Thermochromic (liquid crystal)	Hydrochromic	Photochromic
Dynamic behaviour	Blue dye changes by the warmth of breath to white.	Black colour is changed by the warmth of the fingers to a range of different colours.	White colour is changes to transparent by humidity.	An electronic measures water consumption and UV-LEDs change the blue colour of the dye to red.
Dialogue	"See me breath. Understand the importance of protecting yourself!"	"You can do it. Just follow the path!"	"It is time to water me!"	"You used a lot of water. You better get out!"

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2. Experimenting and Hybrid Concepts in Material Design

by *Markus Holzbach*

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1. Material Design: Introduction

It is the materials that transfer our ideas into the real world and increasingly take over the role of the actual object. Through the materialization of our ideas and design concepts they become tangible. With material design, the role of the material in the design process is discussed anew and the traditional way of thinking of “material-compatible design” is overcome. Today, design concepts are fundamentally influenced as well as digital design and production tools by their materiality in a blending of digital and real. Materials thus become carriers of a wide variety of information and enter into a dialogue with their environment. They become informative, or even intuitive.

Despite digital charging or information, the material can still be experienced - instead of pure digitalization, there is an increased “reanalogization”. Even in the digital world, material has not - as predicted - lost its importance. Despite progressive digitization, it remains the digitization of our world - a physical world. Rather, an increasing overlapping of the digital with the real, i.e. our living world, can be observed. The digital infiltrates the “real” and the physical and material world surrounding us - material particles thus become particles of information. Material particles serve as data carriers.

From the symbiosis of the material with the digital and material-technical changes, hybrid conceptions result, which open up new ways of formal and functional design. The path from static to dynamic and process-oriented properties is thus smoothed (Holzbach, 2014).

2. Institute for Material Design IMD

The Institute for Material Design IMD at the University of Art and Design Offenbach works in an experimental and interdisciplinary dialogue on

the analog and digital intersection of visualization and materialization. In teaching and research, works that in their core deal with the role of material in the design process are conceived in different scales.

The progressive approach of thinking in interdisciplinary processes and seeing material, construction and design as a unity represents a connecting factor for model for many disciplines in our digitized world. Digitization is predestined to bundle such diverse, but mostly different and heterogeneous processes. Only through their visualization and materialization our ideas and design intentions become visible and tangible. These range from material concepts that intervene in the chemistry of the material to the object level in design and experimental architectural and urban concepts. The focus is on adaptive and interactive processes and the design fundamentals of materials, structures and systems. The aim is not a dogmatic reduction but a conceptual materialisation based on a variety of analogue and digital methods and their combination. New “highly charged” materials increasingly take over the role of the actual object.

In contrast to classical product design, in material design the processes and also the basic principles of materials, structures and systems play a decisive role. The aim is to provoke results with a usually high degree of experimental freedom. Often this also has to do with the quest for what is feasible or breaking up design conventions in order to ask a few more questions than provide answers, perhaps also in the sense of Ludwig Wittgenstein. The boundaries of design, architecture, art, technology or science are often no longer recognizable. Many of the works created in this way move at the interface between man and material or nature and artefact. Emerging hybrid forms no longer allow a clear separation or even classification. Partly different and also contradictory materialities and functionalities coexist alongside and with each other. High-tech is linked with low-tech strategies and non-linear storylines are implemented. Materials increasingly have properties that seem to be “alive”. At the same time, natural materials are linked with synthetic materials and digital interfaces and thus transformed into the artificial world. Contemporary design concepts are based on the intersection of digital and real. Materials or hybrid composites with sensitive, smart or gradually varying properties lead to new and complex design concepts (Holzbach, 2014).

3. Material Design - Designing with Designed Materials

The design with material becomes a design of material and in the consequent continuation a “designing with designed materials” (Holzbach, 2015 a).

“If this quite different, far more active role of materials that function like automatons and represent their own operative systems is currently emerging in the context of material sciences, then it is something that will change our entire understanding of materiality and design, of technology and nature. Material and matter will no longer be regarded as passive masses that become the carriers of technical or symbolic operations. Rather, it reveals itself as an active operative system” (Schäffner, 2016; quote translated through the author).

Classical categories of material are increasingly dissolving. Thus Sabine Kraft writes in her article *Materials - Properties as variables*: “The relationship between form and material has become as diverse as it is ambiguous. A recourse to clear specifications as to what can be conceived and constructed in which material and how, and what aesthetic message would be transported by this, is hardly possible anymore - if it ever existed” (Kraft, 2004; quote translated through the author).

The interpretation of material design is also about the integration of material research. Especially the integration of material parameters in digital models, as we see them more and more in design disciplines, originates from the natural science and technically motivated disciplines. Of central importance are not only functional but also aesthetic qualities. What do the texture, aggregate state, elasticity or viscosity of a material tell us? Increasingly systems that are inspired by physics, chemistry or biology are getting developed. A new nomenclature is emerging - materials or hybrid materials receive their information or determination through the manufacturing and forming process or through their compositional joining with other components. The newly interpreted material worlds hence open up a wide range of possibilities for shaping our environment.

The new logic of the material often no longer has anything to do with originally inherent properties. This fundamentally changes the nature of design concepts. While the advent of digitalization initially led to an increased change in drawing and design tools, this was followed by digital production tools and the resulting continuous process chains. The observed linking of the digital with the real or the digital with the material was followed by

hybrid structures with their own hybrid property profiles. This results in a formal and functional charging of existing materials. At this stage, the resulting material hybrids are usually still constructed on a macroscale, visible level and already show “living” or “intelligent” properties. Materials thus become interactive, connective and smart. New generations of digital and also post-digital material hybrids also show the reactive properties of the animated world, but suggest the properties of the “intrinsic”. The pseudointrinsic behaviour is realised by micro-scale and hidden digital or postdigital material charges. The pretended formal and functional properties of the respective material composites are perceived as inherent and seemingly react automatically to their environment. An “empathic logic” opens up the dialogical performance of the material. By placing the materials in completely new contexts, they become hybrid carriers of different information and enter into a dialogue with their environment.

In their 1977 film “Powers of Ten” Charles and Ray Eames in a certain way anticipate the question of scaling and the micro-scaling which is associated with digitization and post-digitization. At the interface between design and science, they, as designers, take a short journey to present the different dimensions of the most distant and largest as well as the very near and smallest structures. As Ray Eames writes: “Charles learned from Eero Saarinen how important it is to look at things from the next largest or next smallest scale” (König, 2005).

4. Experimenting Materialdesign: Case Studies

Many works at the Institute of Material Design IMD are the result of experimental and interdisciplinary processes. With a high degree of freedom, IMD also pursues unconventional paths - the different qualities, possibilities and even impossibilities of materials and their role in the design process are explored. In addition to the digital and analog processes, the special attraction often lies in interdisciplinary, material-unspecific combinations and in the experimental transfer from familiar to unfamiliar contexts. In a very open and experimental methodical understanding, design and materialisation as well as teaching and research are linked with each other.

Andreas Reckwitz writes about the “proceduralization of creativity”:
“Since the avant-garde movements [...] a special interest has been in the techniques, the procedures of the creative process. These now essentially appear as those of coincidence management [...]. It is not the subject that

appears as the original instance of a production process, but it is the process itself that produces something new in its own dynamic. This production of something new can be promoted by certain techniques [...]. For these creativity techniques, the promotion of chance is central - whether in dealing with the material or in the mental sequence of the association. The point is to allow a momentum of processes in which something new is produced [...]. Creativity is then no longer to be identified with a subjective creative power, but amounts to a promotion of unpredictability in dealing with things and ideas” (Reckwitz, 2010; quote translated by the author).

Works are conceived in different scales, which in their core deal with the role of material in the design process. At the same time, the integration of new digital or even material-technical components creates completely new formal and functional contexts - they are informed or overwritten. The observable linking of the digital with the real or the digital with the material leads directly to hybrid structures with their own hybrid property profiles. The following case studies were developed in research and teaching at the Institute of Material Design at the University of Art and Design Offenbach:

Morphing Materials // Magnetic Fabric

The work Magnetic Fabric explores the properties of a textile such as mobility and flexibility. Integrated, magnetically effective components are used according to various parameters and depending on the arrangement of the elements and the nature of the textile, and set the textile surface in motion. The interaction of active and passive units, methodically arranged inside the textile envelope structure and the surface, causes a mechanical attachment of the components and thus a dynamic rearrangement of the entire medium. The behaviour of the textile and the permanent transformation of its shape are initiated by a hidden digital interface, thus suggesting a moving life of the textile itself (Holzbach, 2015 b).



Fig. 1 - Morphing Materials // Magnetic Fabrics Lilian Dedio at Institute for Materialdesign IMD, University of Art and Design Offenbach

Light Skin

Light Skin is the vision of an interactive “skin” in an automotive context. Stimuli such as touch, pressure and vibrations are received via embedded silicone lenses and released as spots of light: touch becomes visible and provides an optical feedback. The display becomes an analogous interface between object and space. Along with its tactile qualities, in an automotive context Light Skin makes it possible to control the car body and use it as an information and warning display in traffic by visualizing physical forces. Centrifugal and inertial forces would then make the vehicle light up in different ways. Light Skin strives to overcome the existing notion of an automobile and re-interpret its function and appearance (Holzbach, Kellner, Gaines, 2014 b).



Fig. 2 - Light Skin, Julian Schwarze, Martin Pohlmann at Institute for Materialdesign IMD, University of Art and Design Offenbach IMD in collaboration with BMW AG “Intuitive Brain”

Hydro Lighting Surface

Hydro Lighting Surface stands for a membrane construction with local function allocation. A resin coating, which is applied to a textile by means of the screen printing process, enables the opposites solid/flexible and hydrophilic/hydrophobic to be inscribed in a textile fabric. The adhesive property of the textile is changed in such a way that water adheres to the printed structures like pearls. Thus the water acts as a control and triggers further functions, such as hydrochromic or thermochromic effects. In this way, the coating reacts to the chemical composition of the water or its temperature and makes hidden things visible. Fluorescent pigments contained in the liquid give the textile a luminosity in the dark, which is further enhanced by the prismatic effect of the drop of water. The luminous textile is always active when water interacts with the textile. The water drop acts as a local conductor of electricity. Where the water can accumulate, the electric circuit closes and an LED starts to light up (Holzbach, 2015 b).



Fig. 3 - Hydro Lighting Surface, Alix Huschka at Institute for Materialdesign IMD, University of Art and Design Offenbach, IMD in collaboration with BASF designfabrik and Hyundai Motor Deutschland GmbH

Transformative Paper

Technical or engineering material parameters are often included in digital models. Today, the materials often undergo digital programming themselves.

Swelling behaviour and the anisotropic nature of machine-made paper (as with wood-based materials) are often a disadvantage, as they do not guarantee uniform properties in different directions. However, if one takes advantage of this, materials can be completely defined and activated individually depending on their preferred direction. In this example, the paper as starting material was combined with another material to form a hybrid structure that leads to new combined qualities. The adaptive structure reacts automatically and continuously to environmental influences and is fed solely by the “intelligent” behavior of the used starting materials. The post-digital approach - in contrast to the previously presented example of Magnetic Fabrics - no longer has a digital interface. The “intelligence” lies in the material itself. The result is a reactive - lifelike - skin that is able to close automatically when it starts to rain. Depending on the humidity of the air, the paper structure transforms into different states - subtly or very clearly. At high humidity, the reactive skin closes completely and begins to glow intrinsically via a further material and not digitally motivated charge. All reactions take place in real time and are reversible. In the case of high dryness, the individual segments return to their original position (Holzbach, 2015 b).

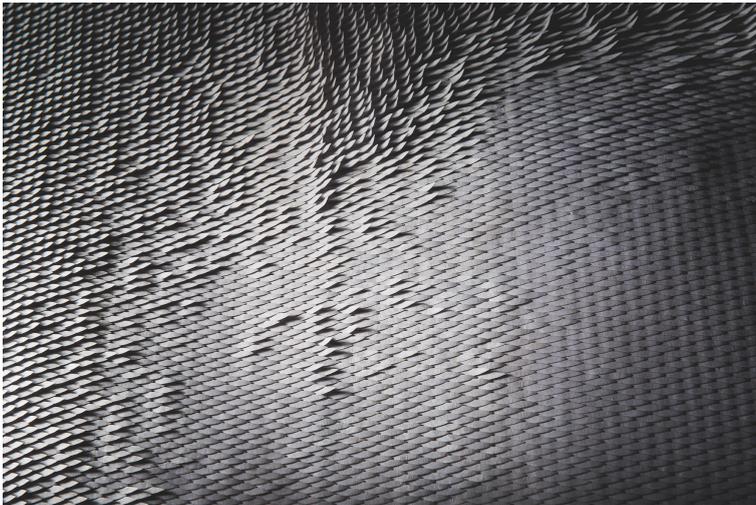


Fig. 4 - Transformative Paper, Florian Hundt at Institute for Materialdesign IMD, University of Art and Design Offenbach, IMD in collaboration with BMW AG “Intuitive Brain”

Engelstrompete

Presented in the Palmengarten Frankfurt the “Engelstrompete” combines low tech with high tech strategies. Natural and artificial components combine to form a light, flat supporting structure made of renewable regional hazel and willow woods and a translucent aluminium membrane. The interactive installation interprets the idea of sustainability, all materials can be easily separated, no environmentally harmful compounds are used or produced. The pavilion of three inflorescences is modelled on the blossom of the Engelstrompete and is composed of 90 cantilevers stressed in bending. The installation has a diameter of 20 metres. The pavilion shows analogies to an organism that reacts to its environment and communicates with it - visually and acoustically. The very light translucent membrane forms the skin between the wooden leaf ribs and at the same time serves as a reflection surface or space for different projections. Moving forms and changing colours underline the analogy to a living organism. The visual level interacts with the visual sound space, which was specially designed for the project. Sounds of nature, the twittering of birds from the surroundings, but also urban sounds, for example from the neighbouring underground railway, are the raw material for the acoustic superimposition and are reproduced in an alienated way. The video projection, which is adjusted to the sound situation, interacts with the metallic shimmering inflorescences that are moving in the wind and changing colour and shape progressions (Holzbach, 2014).



Fig. 5 - Engelstrompete, Luminale Palmengarten Frankfurt am Main, IMD-Team: Aldo Freund, Philip Kliem, Barbara Wildung, Benjamin Würkner, Sound: Dominik Eulberg, Foto: Emily Wabitsch

Hybrid Material and Hybrid Properties

“Hybrid” material solutions integrate digital and material-specific technologies at a scale and complexity that no longer allows conclusions to be drawn about the performance or function of the existing material systems. Many of today’s object and material hybrids follow the approach of sustainability and focus on an intelligence that is not always inscribed in the material itself, but in the way it is constructed, joined and used. The digital in particular is predestined to connect different sensory levels. In the digitalized world surrounding us, concepts are increasingly developing in the intermediate area between Art and Science or Design and Technology. The latest technologies help to move the boundaries of design and artistic potential. Real materials are digitally or procedurally charged, programmed and informed and increasingly possess dynamic and “smart” properties. How much do nature and material interact with the artificially created? The real and the virtual combine in new hybrid forms with their very own hybrid characteristics. How and with which tools can these be described?

The “empathic logic” opens up a dialogical performance of the material. Materials are reprogrammed by placing them in completely new contexts, digitally charging and developing hybrid concepts. Through this information, materials acquire new properties and attributes of “living” or “intelligent”. They become interactive, connective or even smart - they seem to react automatically to their environment. Microscaling thus leads to the suggestion of apparently existing formal and functional properties in the material. The resulting static, dynamic and process-oriented properties, some of them existent together, give rise to new design concepts and, at the same time, important questions. How do different and sometimes contradictory characteristics act and interact in hybrid overall concepts?

This is also the ambivalence of the presented material solutions. Shape and properties are no longer congruent. Articulation of the new material solutions and hybrids will be an important task of material design and creation (Parisi, Holzbach, Rognoli, 2020).

Material Design: Human-Object Communication

Even in today’s blending of digitality and reality, design concepts are fundamentally shaped by their materiality. Through the experimental combination, new design approaches on the level of concept, form and function are actively provoked. These are embedded in interdisciplinary processes that

understand material, construction, form, function and context as a unity. The path from static to dynamic, process-oriented properties is thus smoothed. Through digital or process-related information of materials, their formerly material-specific or “authentic” properties are supplemented, overwritten or completely replaced. This fundamentally changes the nature of design concepts and leads to completely new links of knowledge. “Informed” or “charged” materials with sensitive or smart properties lead to an increasing blending of different contexts. This results in hybrid forms which no longer allow separation. The resulting works often move at the interface of nature and artifact, analog and digital. Where is the border between real and fake, natural and artificial?

Material simultaneously takes on another role – the role of the actual object. Materials and objects of the material world surrounding us are more and more informed. Through this new “charging level”, materials and things are given a new and unique nomenclature - in other words, a hybrid nomenclature. The increasing micro-scaling has already been described by Nicholas Negroponte in “Beyond Digital” as computers “that disappear into things that are first and foremost something else... Computers will be an important but invisible part of our everyday life” (Negroponte, 1998; quote translated by the author).

In classical product design, the instructions for use are clearly communicated through the specific formal training of the sign function. This understanding is essentially based on previous experience, but also - and here it becomes more speculative - on expectations. Are these clear assignments of function still given in the newly coded and informed hybrids? The role of the sign function as a mediator has to be renegotiated especially in the area of “intelligent”, smart and connective material hybrids. The basis of the knowledge mediating dialogue between human and object or also human and hybrid materials lies in experience and recognition. The hybrid material systems no longer convey these distinct characteristics clearly and the idea becomes ambiguous. What are the signs of the designed? What does it represent? How can it be used?

Many of the shown works reside at the interface between materialization and visualization. How can hybrids, which are simultaneously located in the real and virtual world, be described with previous tools? Particularly in completely new functional and technological contexts, specific sign functions are often not recognizable, especially at the beginning. There is just as much potential for new solutions in their redefinition as in their transfer from

other contexts. They are not necessarily based on stored experiences and the resulting recognition. This has a great impact on communication and the perception of the world around us, characterized by a communication that is no longer based on the necessary recognition and mediation, but that may not take place at all - intuition takes the place of instruction.

Outlook “Nomenclature of the In-Between”

Hybrid material systems and objects suggest the properties of intrinsic intelligence or the intuitive. The object or hybrid system decides whether it communicates itself to us. This means that it can no longer be a human-object or human-material relationship but conversely an object-human or material-human relationship. Essential factors for the additional arrival of a dialogue, such as recognition, now start from the object. This recognition is conveyed by different connectivities and data acquisition on the side of the object - with important user data, user recognition, etc., in order to gain knowledge by creating a user profile and to form the basis for an “allegedly” optimal communication through that.

Many of the informed objects and materials are increasingly complex, contradictory and hybrid. They unite different worlds of the virtual and the real, the physical and the non-physical. Just as hybrid materials, objects and materials are characterized by hybrid properties, the tools that describe them individually will also have to carry this hybrid nature within them. The dynamic digitalization of our real environment world demands a holistic theoretical approach that takes into account the different pluralities and realms of the virtual and the real with the interdependence areas operating in between. Due to the increasing developments in science and technology and the growing interconnection of different fields of knowledge in the digital world, the number of indeterminate interdependencies is simultaneously growing. It is necessary to develop a nomenclature for the in-between. This is linked to the task of expanding and further developing the creative and artistic experiment and interdisciplinary permeability and deriving from this decidedly inductive and hybrid theories. Despite all the desire for determination, the degree of variables, discrepancies and transitions is growing - the world is becoming more complex and indeterminate. These uncertainties, however, are also a source of great inspiration and ultimately of great essence for many disciplines and also for design. The opening up to other fields of knowledge and science defines a new scientific claim, according to which design is also to be understood essentially as a cultural task and, as a cross-sectional

discipline in interdisciplinary exchange, that has an active role as an impulse generator and designer of our environment.

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3. Bioplastic Robotic Materialization. Design to robotic production of biodegradable lamps

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A collaborative course between the Dessau Department of Design and the Dessau Institute of Architecture led by Manuel Kretzer and Sina Mostafavi

1. Introduction

Sustainable, ecological, natural, green, organic, healthy, and many more are slogans and keywords we're exposed to on a daily basis. But how sustainable is the content that is being promoted really? And who - after all - can afford to live sustainable? By 2050 the world's population is expected to reach 10 billion people. The fastest growing and largest populations "will be concentrated in just nine countries: India, Nigeria, the Democratic Republic of the Congo, Pakistan, Ethiopia, the United Republic of Tanzania, the U.S., Uganda and Indonesia" (Graham, 2017). Yet almost 15% of India's population still has no access to electricity (BBC News, 2018). In Nigeria only 64% of the population is provided with clean water and 28% with proper sanitation facilities (World Health Organization, 2015). Pakistan's annual waste production is almost 48 million tons, yet there are no efficient collection systems in place so most garbage ends up filling the streets leading to various related environmental and public health problems (Export.gov., 2018). So the terms we seem so familiar with - sustainability, ecology, nature - are in most cases largely related to an ideology of the first world, an ideology of affluence, wealth and capitalism. We buy our food from the organic grocery store because we have access to green alternatives. We worry about putting the trash into the correct trashcan because we can afford to worry about it. But how sustainable are we really? Would we truly give up some of our comforts to save the planet? Would we sacrifice anything of what we're so used to for a better future? And are these even the questions that we should be asking?

Probably not, and most probably that's also the reason why there are still so few truly ecological solutions out there. Being sustainable thus shouldn't

be associated with reduction but should be linked to improvement, or as Timothy Morton, also known as the philosopher prophet of the Anthropocene, explain after converting his home to wind-generated electricity, which meant that he could produce more energy than he actually needed:

You think ecologically tuned life means being all efficient and pure. Wrong. It means you can have a disco in every room of your house (Timothy Morton on Twitter, 2018).

With that in the back of our heads, understanding ecological design as an improvement, an increase on all fronts, not only a product's carbon footprint, we want to shift our attention towards plastics. Plastics, whose main areas of application are in the packaging, building and automotive industries, have in recent years become less and less attractive for the design of products. This is mainly due to their dependence on non-renewable resources, an association with cheapness and a lack of tactile differentiation. But what if we had plastic that wasn't dependent on fossil fuel? What if we had plastic that wouldn't need recycling since it can (bio)degrade by itself? And what if we not only had so plenty of that material that we wouldn't have to worry any longer about where it comes from but what if its properties would also excel those of traditional plastics? What if it would look more interesting, feel more diverse and maybe even smell like something we like? – Bioplastics!

2. A brief history of bioplastics

Bioplastics or biopolymers are substances that are composed of renewable organic biomass sources, such as starch, cellulose or sugar. Because of their biological origin, they are inherently biodegradable, which means that they can easily be broken down into CO², water, energy, and cell mass with the aid of microbes, rendering them largely carbon neutral. On top of their ecological advantages to standard plastics, which are mostly derived from petrochemicals and can take hundreds of years to degrade, they help to conserve fossil raw materials and the dependency on mineral oil.

The origins of bioplastics can't be exactly set, but natural resins, such as amber, shellac, or gutta percha, have already been used during Roman times and in the middle ages. Commercial production of bioplastics started in the middle of the 19th century. In 1845 the Swiss-German chemist Christian Friedrich Schönbein created a robust, clear and waterproof cellulose derivative from paper (cellulose nitrate). In 1846 Louis Ménard found out that drying a solution of cellulose nitrate and ethanol, called collodion, would

result in a tough, elastic and waterproof material. In 1848 J. Parker Maynard applied collodion on open wounds and discovered that it dried into an air- and watertight film that advanced the healing process. At the 1862 building exhibition in London the English inventor Alexander Parkes displayed a pressure-moulded product from collodion, which he called Parkesine. In 1869 John Wesley Hyatt Jr. patented the use of collodion for glazing billiard balls as an alternative to expensive and precious ivory. Together with his brother they developed a process for plasticizing cellulose nitrate with camphor in 1870 and subsequently opened their first factory to mass-produce what they called celluloid. Celluloid became largely popular in 1882 to create photographic films and later for making the first motion-picture films. Towards the end of the 19th century Adolf Spitteler, a Bavarian chemist, invented mouldable casein plastic, a material that was durable, corrosion-resistant and soon became a strong industry. In the 1910s Henry Ford experimented with using soybean plastic for the use of automobile parts, and in 1941 he presented a prototype car, whose body consisted of fourteen pressure-moulded parts made from soybean plastic. In 1923 the industrial production of cellophane began, the only bioplastic that to date survived the rise of the synthetic plastic industry. Cellophane is a sheet material made from cellulose, which is found in plant cell walls and makes up around 40% of all organic matter. Since the 1980s, due to growing environmental awareness, research and development into bioplastics have resumed and are constantly increasing.

Yet, bioplastics still have a long way to go until they are able to seriously compete with their petrochemical rivals. Mostly the two to three times higher cost in production but also the fear of losing land for the growth of food or accelerated rate of deforestation hinder its economic development. Similar concerns exist over its impact on water supply and soil erosion. Since the building and construction industry is among the largest consumers of plastics, the potential of less pollutant plastic alternatives is fairly obvious. However, the biodegradability of bioplastics poses a major problem and currently results in applications mainly reduced to the interior or of a temporal character (Kretzer, 2017).

Do-it-yourself bioplastics

Generally all plastics can be described using the following equation:
(bio)plastic = (bio)polymer + plasticizer (+ additives)

Roughly speaking the polymer gives plastic its strength, the plasticizer is for its elasticity, and the additives provide additional properties such as colour, durability, etc. In most of the following recipes, glycerine is used as

the plasticizer, defining the plasticity of the respective material; accordingly the following rule should be remembered: less glycerine will create a more brittle but harder material; more glycerine makes it more flexible and softer.

All recipes are adapted to a volume of 200 ml water however the quantities can be adjusted. Standard tap water can be used but distilled water might lead to more consistent results.

Gelatine based bioplastic

200 ml Water / 40.0 g Gelatine Powder / 10.0 g Glycerine

The mould can be made from cardboard or any other material. It is however essential that the form has no holes or weak parts to prevent leaking of the liquid bioplastic. More complex shapes can be designed, but depending on the thickness, the material can take very long to dry fully. Mix the cold water with the gelatine powder and glycerine in a pot. The mixture has to be stirred until no clumps remain, and it is as dispersed as possible. The mixture is then heated, while continuously stirring, up to 95°C or until it starts to froth. Once it has reached its peak temperature no more heat should be added and excess froth removed with a spoon. Once the solution is ready, and no more clumps remain it can be poured into the previously prepared mould. Aluminium foil can be placed underneath and greasing the mould with vegetable oil will help to release the plastic after it has hardened. The liquid should be equally spread across the surface. The amount of time it takes to dry strongly depends on the thickness of the final product as well as the temperature and humidity in the room. It might take several hours or even days until the sheet has fully dried, a toothpick can help to check its state. Once it is ready, the sheet can be carefully removed from the mould using a knife or scalpel and then be further processed.

Alternative: Thin Sheet Recipe: *200ml Water / 7.5g Gelatine / 4.0g Glycerine*

Starch based bioplastic

200 ml Water / 30 ml white Vinegar / 15.0 g Glycerine / 70.0 g Starch

The water, vinegar, and glycerine are poured into a pan or pot and mixed. Cornstarch is added, and the solution thoroughly stirred, while slowly adding heat, until it has completely dissolved. After continuously mixing and heating the liquid for about ten minutes, it begins to thicken and turns gel-like. The heat can then be turned off, but the gel should be stirred for another one

to two minutes before pouring it into a mould or on a flat surface. The material needs between twelve to twenty-four hours to dry, heavily depending on its thickness. Serious shrinkage might occur. The amounts and volumes can be adjusted in order to create materials with varying properties. More glycerine will result in a harder plastic, and more starch makes for a denser and less viscous material.

Alternatives:

1. Best for filling moulds and easier to work with: *200 ml Water / 25 ml Vinegar / 25.0 g Glycerine / 35.0 g Starch*
2. *200 ml Water / 6.0 g Baking Powder / 16.0 g Starch / 30.0 g Vinegar / 25.0 g Glycerine*

Starch does not make for a very sturdy plastic. It can be used to create thin, flexible films but is generally too weak to make solid objects like cups or utensils.

Casein based bioplastic from milk

200 ml Milk / 1 tablespoon white Vinegar

The milk has to be slowly warmed in a pan or pot. The vinegar is added while the milk is continuously stirred until solid clumps begin to form. The liquid is then poured through a strainer. The remaining clumps can be scooped out and left on a flat surface covered with kitchen paper. Kitchen paper is also used to press out excess moisture. The material will need several days if not weeks to dry.

Casein based bioplastic from cream and lemon juice

200 ml Heavy Cream / Lemon Juice

The cream is mixed with five tablespoons of lemon juice in a pan or pot. The mixture is then slowly heated to simmering over low to medium heat while continuously being stirred. Gradually more lemon juice is added. The mixture will eventually thicken and make a gel-like consistency. Remove from heat and allow it to cool down. After straining the mixture, the solid cream by-products can be collected and washed. They can then be moulded or shaped into various forms. Casein based bioplastics take very long to dry and - although hard - remain rather brittle.

Algae bioplastic

Agar Only

200 ml Water / 20.0 g Agar / 3.0 g Glycerine

Agar-Starch Blend

200 ml Water / 1.0 g Sorbitol / 2.0 g Starch / 0.5 g Agar / 1.0 g Glycerine

Gelatine-Agar Blend

200 ml Water / 2.0 g Sorbitol / 2.0 g Gelatine / 2.0 g Agar / 1.5 g Glycerine

The procedure is basically the same in each case. All of the above ingredients are mixed and stirred until no clumps remain. Then the mixture is heated to 95 °C or until it starts to froth. Excess froth needs to be scooped out with a spoon. It can then be poured into a mould or onto a flat surface and left to dry, which may take several days.

Algae bioplastic produces a pretty good hard, inflexible plastic as long as a very small amount of plasticizer is being used.

3. Bioplastics and robotic fabrication

In an experimental and do-it-yourself context, the availability of raw resources for making various types bioplastics introduces challenges and opportunities of working with more creative and customized methods of fabrication. Similar to the ideology of fab-labs (Gershenfeld, 2011) and the maker movement, this requires interdisciplinary studies involving geometry, parametric design modelling, fabrication technology and the design of material behaviours and properties. In order to provide such a broad working environment, a collaborative course was framed between the Dessau Department of Design and the Dessau International Graduate School of Architecture (DIA), to explore the potentials of do-it-yourself bioplastic materials in combination with cutting-edge robotic fabrication. The overall task for the students, who worked in teams of four to six people from both fields, was to design and produce biodegradable lamps. Yet, beyond the physical creation of the objects, the aim was to both master the material system and establish a tailor made robotic production routine for each specific bioplastic material set.

Recent advancements in digital design and robotic materialization have introduced innovative methods for the realization of complex geometries and direct experimentation through physical prototyping. The flexibility and programmability of such techniques allows for the implementation of alternative materials in various scales ranging from product design to building processes. In this context, architectural robotics, as an emerging field, facilitates novel means to incorporate informed materiality in building processes and

products. Consequently in the particular context of working with bioplastics, the efficiency of the design can be achieved by engineering the complexity of material distribution and controlling the degradability level of the used material itself (Mostafavi, 2018).

4. Projects: Design to robotic production of biodegradable lamps

Changing customs - Vegan Bioplastic Chandelier

Veganism is a philosophy and way of living which seeks to exclude - as far as is possible and practicable - all forms of exploitation and cruelty to animals, either for food, clothing or any other purpose; and by extension, promotes the development and use of animal-free alternatives for the benefit of humans, animals and the environment. While the group's focus on veganism is expressed directly through their bioplastic material, which doesn't include animal gelatine, they created a design that makes people aware that humanity's current customs are a problem, especially for future generations. Based on this idea the team worked with two basic design principles; variants in height to emulate the topography of Planet Earth and surface subdivision to represent individuals and population. In each cell a Led point light was placed before casting the material into the robotically produced mould. As pictured in Figure 1, an interesting feature to this design is the way the impurity of the material mix creates ranges of translucencies as the light travels through the solidified plastic. However, the lifespan of this recipe is significantly lower than the mixtures of other groups.



Fig. 1 - Vegan Bioplastic Chandelier; Variation in height and thickness results in shades of brightness and saturation of each cell

Second Skin

The concept of this group focused on the idea of making us feel more human in the future. In a world where algorithms and artificial intelligence surround and control everything, it could become normal to interact with machines that simulate feelings. Thus this project - which suggests a second skin encapsulating our body - is supposed to show and remind us of our true selves by displaying real emotions. By combining bioplastic with thermochromic pigments, the group created a material, that turns white when reaching a temperature above 34°C and hence reacts to the body of the person wearing it. The product is thus able to detect and record for example physiological signs of stress and excitement by measuring temperature changes in the skin and is, therefore, able to communicate human feelings that might otherwise remain invisible. A series of material and fabrication tests were conducted to test different recipes as well as various geometric patterns. The production process implemented a round blade cutter mounted on a robotic arm (Figure 2). After preparing and cooking the customized bioplastic, the relatively viscous material was laid down on flat trays. A parametric design to production model accompanied by a robotic simulation made sure that the cutting pattern was producible. Variation in the lengths and directions of the cut resulted in a porous garment. The porosity, as well as the outline shape of each part of the garment, was informed by the local curvature and temperature of the human body.



Fig. 2 - Second skin; a three-dimensional and porous garment using robotic cutting of flattened bioplastic sheets with varying patterns

Fruit Lamp

Starting from the necessity to develop more sustainable solutions and looking at nature for inspiration, this group designed and produced a lamp that resembles natural forms, which due to its biodegradability could become directly integrated into existing tree structures. In addition to the environmental friendliness of the product, the group integrated a gravity pulley mechanism, which allowed the lamp to be illuminated without the necessity of external electricity. The lamp can thus be placed and used independently from access to an external electrical power supply. Several tests were done with robotic milling to find the right geometric properties and proportions. Moreover, it was essential to ensure consistency and stiffness as each of the elements transforms from a flat surface to a curved one. Therefore, coffee grounds and powdered leaves were added to the mixture (Figure 3).



Fig. 3 - Fruit Lamp; Biodegradable lamp blended into a tree structure, equipped with a gravity pulley mechanism, makes it independent from the need of an external electricity source. The moulds for each piece are robotically milled

Lifelight

Lifelight is a concept, which is ought to make the parting from a loved one easier by transforming the unpleasant experience into a process of renewal and becoming. Based on the idea of the life cycle, the design started by using a circle in plan view onto which different emotions and moods of the diseased (hypothetically collected over their lifetime) were mapped, gradually turning the basic shape into a complex array of overlapping patterns. Regarding the production technique, the group focused on experimental 3D

printing, which was made possible due to the particular material recipe they developed (Figure 4). The fabrication and material research in this project demonstrate the promising potential of bioplastics for additive manufacturing. Eventually, successful prints were possible through an extensive set of experiments and step by step documentation of key parameters such as the viscosity and temperature of the paste, the size of the nozzle of the custom-made robotic extruder, the height of each printing layer, the speed of the servo motor pushing the material, and the robotic toolpath speed.



Fig. 4 - Lifelight; Using digital design and robotic fabrication the team developed a Robotic 3D Printing system for a custom made printable material mixture

Araneo

Lighting accounts for a large percentage of global electricity consumption and considerable percentage of worldwide greenhouse gas emissions. At the same time, an estimated 16 percent of the world's population lacks access to modern energy services. Light is one of Germany's most energy-consuming fields in terms of power usage. One percent of all electrical currents in

Germany are used to power streetlights and guidance lights and about 40% of all power generated in Germany is made in lignite-fired power plants. In addition to the power usage, light pollution became a massive problem in larger cities. The Araneo project thus proposes a different approach towards urban lighting to create less wasteful products and a more comfortable atmosphere for pedestrians. Araneo is a self-luminescent lighting system, made from a highly flexible biodegradable material, which makes it easy to be applied on basically any given surface, like trees, walls or ceilings. The project was produced using a very fine and highly detailed robotically manufactured mould. After having a series of one-to-one scale tests on various moulds with different morphologies and sizes, the final outcome reached 1.2 meters in length and width (Figure 5).

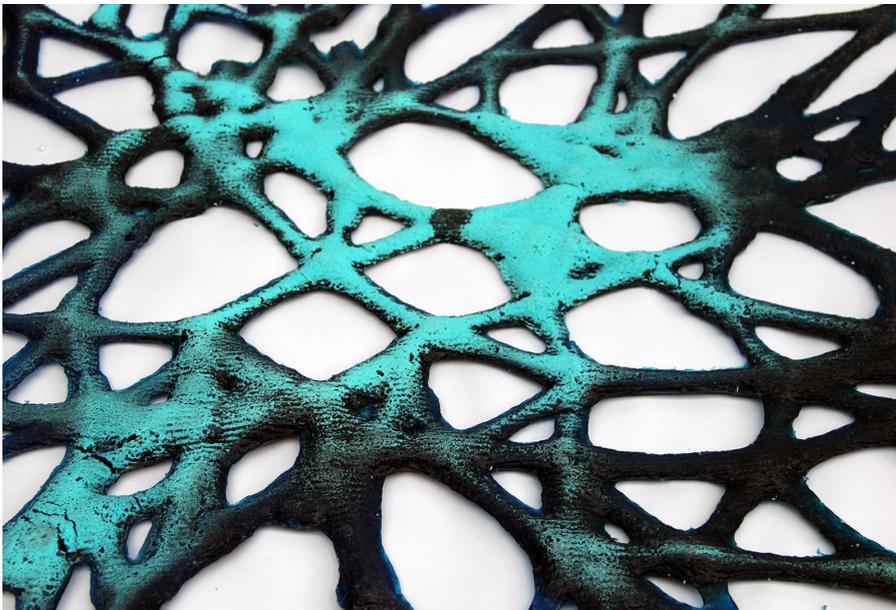


Fig. 5 - Araneo; an alternative urban lighting proposal with self-illuminating additive

5. Conclusion

The overall learning objective of this course was twofold. On the one hand, the participants got acquainted with the fundamentals of parametric design to robotic production. On the other hand, they performed systematic scientific experiments with bioplastics to develop the perfect material recipes

for different robotic production methods. Following a phase of experimental research, the overall goal was to design and robotically produce lampshades made from self-made bioplastic material. According to the outcomes of the experiments and design explorations, relevant techniques of robotic fabrication such as multimode (Mostafavi, 2019), subtractive and additive manufacturing were used.

However, besides the technical skills that the students were introduced to, they learned how to work in cross-disciplinary teams, an ability that will prove vital for their future development. As mentioned during the introduction to this paper, our world is rapidly and massively changing, and we're facing unprecedented challenges on a daily basis. We believe that only together, through unbiased collaboration beyond restrictive structures and rigid boundaries, through open-minded exchange and playful exploration, we will be able to address these issues in a progressive and productive manner. Merging distinctive individual competencies towards a common goal and learning how to communicate and cooperate outside the personal comfort zone represents a key strategy to prepare ourselves for today's and near-future societal and environmental challenges.

In order to elevate this preliminary, highly experimental research to the next level, we would like to focus on the concept of bioplastic robotic 3D printing. As explained in the recipes section, the distinctive properties of a given bioplastic material can be tailored by adjusting its base quantities. Simply speaking, more glycerol makes for a softer, less glycerol for a harder material. If these quantities could now be numerically adjusted on the fly, while extruding the plastic material, we could create a hybrid materiality with varying properties in different zones. While with the basic recipe, this might just affect the material's flexibility, natural additives; such as coffee grounds or banana peel can influence its colour, transparency, structural integrity etc. Obviously developing a robotic end-effector system that would allow for such complex manipulation is highly ambitious and far beyond the scope of a student course but nevertheless it is a fairly exciting and promising point of departure for future research.

A short video provides more details on the course and its individual outcomes: <https://vimeo.com/316313945>

Acknowledgments

We acknowledge contributors as follow:

Tutors: Manuel Kretzer, Sina Mostafavi

Assistants: Mohammed Saad Moharram, Arise Wan

Robotic workshop support: Carl Buchmann

Video: Esteban Amon, Dokuteam HS Anhalt

Students: Changing customs - Vegan Bioplastic Chandelier: *Tania Sabrina Ortiz Ramirez, Delta Carolina Gómez Linares, Valmir Kastrati, Louise Meyer, Marie Philine Frances Rockmann, Tang Yuanfeng* / Second Skin: *Johanna Müller, Dominique Lohaus, Amro Hamead, Neady Oduor, Quenna Leer* / Fruit Lamp: *Hos-sameldin Badr, Kyanoush Bitafaran, Juan Antonio Herrera Gonzalez, Ludwig Epple, Erik Scherenberg* / Lifelight: *Luise Eva Maria Oppelt, Martin Naumann, Julia Ziener, Adib Khaeez, Kamal Amgad, Jason Hage* / Araneo: *Toni Pasternak, Anian Till Stoib, Iwan Mazlan, Mohamed Mansour, Jakob Emmerling, Gulfia Kutlahmetova*

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4. Sustainable Design, biomimicry and biomaterials: exploring interactivity, connectivity and smartness in nature

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Even if it's on the lips of many, the word Sustainability can be a confusing concept, especially in the age of complexity (Faber et al., 2005). In environmental terms, the threshold to be reached gradually slips, as we better understand the functioning of our planet. Nowadays we define sustainability as a dynamic learning process (Wahl, 2016), so design for sustainability (DfS) has changed accordingly, adopting over the years new approaches and methodologies, for example moving the focus from end-of-pipe actions to research and innovation efforts during the very early stages of design (Vezzoli, 2018; Ceschin and Gaziulusoy, 2016).

Within this learning process, it is not uncommon to take direct inspiration from the work of nature itself, with its astonishing 4.5 billion years of ingenious solutions to the many problems of staying alive. The imitation of nature, indeed, has always been a key and innate component of human activities; yet nowadays, thanks to the advancement of scientific disciplines and observation tools, we clearly observe and analyze how extremely detailed, interconnected and fragile is the system we are (a very impacting) part of.

The most fitting example of this DfS attitude is Biomimicry, a practice that refers to nature as model, measure and mentor, while searching for solutions to human problems (Benyus, 1997). This approach involves three levels of mimesis: the mimicking of natural form, where natural shapes and mechanisms are copied (e.g. bio-inspired nanomaterials); the mimicking of processes, for example production methods such as biofabrication (which I will explain later); the mimicking of ecosystems as organizational models for a variety of disciplines (economical, organizational and social issues among others). In this last category we find the roots of a new regenerative production model inspired by the material flows and closing loops occurring in natural ecosystems, which also influenced design approaches such as systemic design (Bistagnino, 2009) and Cradle to Cradle (McDonough and

Braungart, 2002). Both these approaches aim for an industrial system with closed material loops, trying to eliminate the negative meaning of “waste”, while enhancing the missed opportunity to recover it (as suggested by the etymology of the english word: from the Latin “Vastus”, meaning unemployed, uncultivated); the same happens in nature, where the waste of an organism becomes nutrients for subsequent metabolic life cycles.

Circular Economy arises from the same biological metaphor, where the technological and biological materials flows should be always balanced and regenerated. Since the technological materials are not all so efficient in regeneration due to loss of performance in recycling and still unbalanced flows in the market (Cullen, 2017), a more important goal is keeping the value of products, components and materials over time (Ellen MacArthur Foundation, 2013), requiring a new shift in DfS guidelines more focused on design for durability (den Hollander et al., 2017). A different economic challenge awaits biological resources: here, the prefix bio- is used to define materials with an organic origin, naming today an entire expanding sector which is precisely that of the bio-economy: an economy based on the production of renewable biological sources, where the wastes have the ability to enrich their environment of origin. It would be wrong, however, to think that the greatest virtue of these materials is their organic origin, primarily because waste or emissions derived from biological materials are not necessarily sustainable, nor are these waste intrinsically good or healthy (Reijnders, 2008), but it all depends on the industrial symbiosis which, as for an ecosystem in nature, has to manage and transforms materials flows, ensuring a balanced cycle in input and output.

The prefix bio- defines a vast and blurred panorama of specific terminologies also in other sectors: take for example the term biomaterial, born in the medical field to define living cells fabrication or repair; the same word in a design context is the basis of a pioneering, multidisciplinary and visionary approach, born from the growing evidence of environmental damage caused by a linear system and a renewed feeling of safeguarding and union with the natural world. This awareness moved some designers to cross-pollinate their work with others scientific disciplines, imagining and suggesting revolutionary productive scenarios characterized by a nascent biophilic imagery (Söderlund, 2019). This design practice is defined Biodesign (Myers, 2012), with the related term *biomaterial* implied most of the time to describe living beings/organisms/tissues and their special relationship with the designer. Biodesign reaches a deeper level of involvement with nature, going from being inspired by it to the integration of living organisms as functional components in the final design piece (therefore replacing mechanical production methods with biological ones - namely *biofabrication*). The break with the

classical discipline is such that we can find many examples of speculative design (scientific-fact-based) alongside already tested - sometimes even on the market - disruptive and sustainable solutions.

The aim of the present chapter is to focus on this potential, trying to see how it can fit in a broader context where design reflects on itself to the point of questioning its very material side while expanding towards unprecedented meanings; I will try to frame the biodesign wave into the ICS materials, addressing the words interactivity, connectivity and smartness under different perspectives and trying to describe the chance that lies behind an interactive dialogue with the natural world in terms of biofabrication.

1. Biomaterials' inter-activity

From its latin root, every “action between” two entities is an interaction; to achieve it, some sort of comprehension or shared language (even unspoken) is necessary among living organisms, hence becoming suddenly the basis for a relationship. The co-design between designer and living organisms, at the basis of Biodesign, is the first interesting feature of an expanded meaning of the word *interactivity*. The living material is not passively shaped but instructed, albeit with basic instructions. Most of the times such set-up traces the creative boundaries along which the organism can express itself, with different degrees of freedom depending on the speculative character or feasibility of the project. More than one designer working with the mycelium, for example, left mushrooms grow on the surface of the final object, making somehow the final piece unique and characterized by a deliberately wild flavour (e.g. *Mycelium Chair* by Eric Klarenbeek, 2013; *MYX lamp* by Jonas Edvard, 2014). As mycelium started to be known among design's most experimental community, the initial speculative touch gave way to velvety but more homogeneous (and anonymous) surfaces, as requested by an industrial scalability: the biomanufacturing process of mycelium-based products (packaging, panels, leather-like materials among others) is now somehow hiding the distinctive signs of the living matter, leaving the details of its origin and sustainability to corporate communication.

Another aspect varies in this interaction, according to the degree of experimentation: the more radical (or ancestral) the project is, the more intimate the relationship with the organism is usually perceived. The observation of the material growth is associated with a feeling of “care”, as if the biodesigner were in the presence of a pet, to the point that many practitioners, empathetically aware of the work done by the organism, admit its design co-authorship

(Camere and Karana, 2018). The oldest example of such an intimate relation in design is perhaps the longest ever recorded between humans and other living forms, too: in the northeastern Indian state of Meghalaya, indigenous people use *Ficus Elastica* for the creation of so-called *living root bridges*, particularly useful since the very rainy territory is full of rivers that has to be crossed to guarantee basic mobility. The aerial and strong rooting system of these plants, placed on the side of a river, is gently directed - thanks to the skillful weaving developed by the Khasi people - towards the opposite bank, until it joins another planted in a specular position, finally building a bridge. This procedure can take more than 15 years to be completed (Myers, 2012) but the relationship between the living plants and their weavers will probably last for generations (of humans). Shifting to a more serialized perspective, it's worth noticing examples of engineered living plants in the shape of chairs, tables and lamps by the UK company *Full Grown* (research started in 2006 by Gavin Murno): here the process takes less time, but still a chair needs 7 to 9 years (depending on the species) to properly grow. The subtle criticism of fast, irrational and unaffectionate production makes us re-evaluating the time factor as a value: the goal is not a chair for everyone, but one for those who can wait for the chair. In 2013, with the exhibition *Alive: New Design Frontiers*, Collet drew five strategies to design with the living, linking the idea of "Nature as a co-worker" to the concept of designers as new artisans (Collet, 2013): perhaps taking/waiting the right time will be the most useful lesson to remember when the confidence eventually taken with bio-co-authors will make us want to pick up speed again.

Slow and gentle should be also the gesture that accompanies the lamp *Ambio*, the bioluminescent interactive light installation by Teresa van Dongen (2014), full of micro-organisms that emit a moving dim light when lulled by the human gesture, thus provided with oxygen. We can see this pheno-



Fig. 1 - Credits - Full Grown

menon in nature in seawater every time the bioluminescent phytoplankton is shaken by a wave, emitting light as a defensive response. In order to activate the lamp *Latro* (Mike Thompson Studio, 2010) the user is invited to breath into a transparent container filled with algae, thus feeding them with co2; at this point, since the sunlight activates the photosynthesis process, the release of small amounts of electricity will light a bulb. In these two case studies, even if the user is asked for a gentle interaction with the object (like cradling and blowing), these organisms are simply reacting/responding to an external stimulus that would anyway occur in nature. So not only the relationship between life forms, but also the ability to interact with the external environment may be named *interaction*: this will be the second lens under which we will see this word, framing those biomaterials reacting to external stimuli. The pine cone effect, very well known in biomimicry, describes the opening and closing of the “scales” according to weather conditions: usually shut to keep the seeds safe from cold temperatures or hungry animals, the scales open when the climate is hot and dry. Interestingly enough, behind this movement there are just dead cells, folding thanks to structural behavior like the hygroscopic response; typical of wood, this peculiar movement has been already tested in some experiments of programmable materials (Correa, 2014; Zuluaga and Menges, 2015). There are also bacteria reacting to the wet/dry combination, like the cells of *Bacillus Subtilis*: known in Japan for traditional soybean fermentation, they have lately been used as humidity sensitive nanoactuators in the project *bioLogic* (MIT, Tangible Media Group, 2015). Here the bacteria have been assembled with fabric by a micron-resolution bio-printing system, and transformed into a responsive tissue able to expand and contract to body heat and sweat, opening flaps around heat zones (Yao et al., 2015). Although research is still at the beginning, the ability of this bacillus to contract letting our hot skin breathe has attracted a lot of attention from the fashion industry; this is precisely the magic of these first material demonstrators, giving us the opportunity to imagine a future of new application scenarios. It is also thanks to this intrinsic ingenuity (hidden in the simplicity of low tech/energy/cost/impacts biotechnologies) that designers are finally able to create “what if” scenarios while experimenting with living matter, aiming at changing the way we interact with it.

2. Connectivity in the web of life

Fritjof Capra stated that “Whenever we look at life, we look at networks”, referring to the systemic thought, where each unit is a network of relation-

ships inserted into larger networks (Capra, 1996). These relationships, which we could call “connections”, are at the basis of all ecosystems’ organization and of many material structures. Starting from this principle, also this paragraph will expand the meaning of *connectivity* via two different meanings: one on a purely material level, the other related to an organizational level (thus framing the trend of design cross-pollination with other disciplines).

Accordingly with the first meaning, we can notice how some organisms act as a sort of connective tissue, binding together inert material or forming new one out of a liquid medium. This is the case of some bacteria which spin microfibrils of pure cellulose during fermentation, growing a layer of skin-like material. Speaking about bacterial cellulose, a pioneering milestone in the biodesign community is the work of Susan Lee with the project *Biocouture* (2010), employing a symbiotic culture of bacteria and yeast fermenting tea (traditionally used to prepare Kombucha); here the *Acetobacter xylinum* forms a cellulose pellicle on the top of the tea broth, which can then be dried to obtain a leather-like material. One of the limitations of this material was its hydrophilic nature (99% of the constituents is water), overcome by an Italian research team from the University of Salento that developed a particular surface treatment, which makes it hydrophobic producing a bacterial cellulose fed with waste from agro-industry. The same research group is now experimenting with the cellulose obtained in the medical field as wound healing, by empowering with silver nanoparticles the porous and three-dimensional web-like network created by the bacteria (Pal et al., 2017).

Another phenomenon that sees bacteria as a secret glue is called biomineralization, the process by which living organisms produce minerals: this is such a common phenomenon in nature that all six taxonomic kingdoms contain members that are able to form minerals (our bones included). The bacteria *Sporosarcina pasteurii* is able, through a chain of chemical reactions, to form calcium carbonate; thanks to this process, called microbially induced calcium carbonate precipitation (MICP), these bacteria have been added to cement obtaining a *Bioconcrete* (Jonkers, 2011), in which they can improve duration and quality of the material by automatically filling any fissures may occur over time, thus obtaining a self-repairing construction material with evident environmental advantages. A French company, *Biomason*, has developed a *biocement*® which instead of burning calcium carbonate to form cement, grows it with the help of *Sporosarcina pasteurii*; together with recycled aggregates, the bacteria create bricks and tiles without the use of high temperatures and the consequent environmental impact. The same bacteria has been experimented by Damian Palin in the project *A Radical Means*, prototyping a basic stool testing a microbially induced casting procedure (Myers, 2012). The friendship with bacteria is long lasting for Palin, so that he is now wor-

king with them in a more sophisticated biological mining process, obtaining valuable minerals from desalination brine, a toxic byproduct of desalinating seawater, therefore reducing the impact of this technology which is expected to increase in the near future. The fascination for biomineralization impacted also on the architect Magnus Larsson, who envisioned a speculative architecture scenario made of Sahara sand and *Sporosarcina pasteurii* in the building of a 6.000 km long structure, to prevent desertification and the spread of the desert while providing cheap and sustainable shelter for humans and vegetation (Larsson, 2011).

Also Mycelium, the vegetative body of fungi, is an excellent connector: it can easily grow in a substrate of agricultural or wood wastes, growing while eating them, thus expanding through an intricate network of hyphae, connecting all the fibers together. Taking advantage of this voracity it has been used to shape light and porous materials, suitable for the packaging sector (e.g. *MycoComposite™* by Ecovative), or compact and hard board shaped ones, replacing the glue that usually forms plywood panels (*MycoBoard™* by Ecovative). The company Mikoworks is producing *Reishi™*, growing mycelium in layers, obtaining a leather-like material taking the name of the mushroom it is made from. The ability to customize these materials' properties depending on the chosen nutrient substrates of the mycelium, together with its intrinsic sustainability, is what makes this organisms interesting in



Fig. 2 - "Bio Ex-Machina" project ©Officina Corpuscoli & Co-de-iT

various scale applications (Haneef et al., 2017). Introducing the mycelium I mentioned so far case studies where the bioproduction still followed the restrictions of the old manufacturing methods, for example employing molds for the three-dimensional pieces and tanks to achieve a sort of lamination given by the growth in liquid mediums. Speaking of connectivity, even in technological terms, the most ambitious state-of-the-art project is *Bio Ex-Machina*, a collaborative effort by Officina Corpuscoli and Co-de-iT, which introduces the powerful variable of the digital manufacture and the potential of the mathematical calculation, however allowing living matter a certain form of expression; in fact, mycelium does not grow inside a mold or a tank, with predetermined spatial limits, but, thanks to 3D printing, it expands starting from the surface of the printed material, potentially contributing to the final aesthetic. The first experiments of the project by printing modular pieces also confirmed the biological join ability of the mycelium while growing (i.e. biowelding). Here a computational design approach connects designer, code, machine and living matter in a system with many degrees of freedom, both in terms of testing and predictive modeling within the software, and - thanks to the additive manufacturing - of a newfound freedom of form which will trigger innovation and the realization of bio-inspired shapes, notoriously complex and difficult to obtain with traditional production techniques (Polini et al., 2020).

The intertwining between disciplines seems crucial for innovation and it is for sure at the basis of biodesign: a discipline in which the designer must necessarily connect with other disciplinary areas, to the point that he often wears a lab coat for his design research. Oxam saw in the cross-pollination between science, engineering, design and art a perfect match: the first two disciplines process knowledge into solutions, design transforms human experience in behavior while art, by questioning human behavior, ultimately creates new perceptions of reality (The Krebs Cycle of Creativity, Oxman, 2016). In Biodesign the outcomes are often between design and art, taking on a speculative aspect which doesn't refer just to their ephemeral side (from a production point of view), but has also a critical component, aiming at questioning the present time and letting new scenarios emerge.

3. Smartness without a brain

Our fascination for the natural world is both a way to get to know ourselves and a recognition of nature's intelligence, which is therefore beyond doubt; this applies to all life forms, even the smallest ones without brain and

whose “central computer” still remains partially unknown to us. We saw how smart can be bacteria, which as the oldest living form on the planet, have heavily shaped it - exercising their creativity as the main architects of this planet long before the arrival of vertebrates. Thus having a brain is not fundamental when talking about smartness: further proof of this is provided by the slime mold, a single-celled organism, which proved to have a reliable and cost-efficient network construction ability, based on its feeding aptitude, perfected after countless cycles of evolutionary selection. This simple organism has been tested to find the minimum-length solution between two points in a labyrinth, where it easily found a solution without even retracing its steps (Nakagaki et al., 2000). To deeply test its skills in network construction, the slime mold has been put in the center of a map of Tokyo where each train station was represented by a oat flakes (a more interesting destination from a slime point of view); the mold built a network that was comparable in efficiency, reliability, and cost to the already existent Tokyo’s train network, with the exception of having taken much less time and professionals’ brains to achieve a similar result. Given its effectiveness, the logic behind this adaptive network formation has been captured in a biologically inspired mathematical model, to help guide further network construction (Tero et al., 2010). Slime mold has also shown to remember and somehow learn, manifesting habituation abilities, considered to be the simplest form of learning (Adamatzky, 2009; Vallverdú et al., 2018). This primitive cognition is useful to both understand how smartness has evolved in life forms and to develop bio-computing devices (Adamatzky, 2009).

Another species that we know to be very smart are plants: in one of his last books Charles Darwin already recognized plants as intelligent organisms (Darwin, 1880). Plants detect and respond to many environmental signals, evaluating them to optimize access to resources distributed in the surrounding environment; also in this case brain is not necessary for intelligent capabilities, while the root systems have shown incredible smart potential. Dutch designer Diana Scherer takes advantage of the ability of the roots to navigate following intricate paths in her project *InterWoven, exercises in rootsystem domestication*, started in 2012. She first observed the movement of the roots in the pots for a previous project, thus wondering if she could weave roots underground. Working with oat and wheat seeds, whose roots grow quickly, she guides them through texturized molds that act as templates. The end result is much more similar to a woven fabric than to the random root system we usually imagine taking place underground. Scherer’s work is now exploring the world of fashion, moving the harvesting of plants to a new level, although it is difficult to say who/what has tamed whom/what. In fact, plants balance co2 flows on our planet, their photosynthetic action provide

us oxygen and they are the basis of the food chain, just to mention some of their most valuable skills which helped many life form to evolve. Emphasizing our co-evolution with plants and the active role of connections we both have in influencing the climate, researchers Baluška and Mancuso stated that «Considering plants as active and intelligent agents has therefore profound consequences not just for future climate scenarios but also for understanding mankind’s role and position within the Earth’s biosphere» (Baluška and Mancuso, 2020). Becoming aware of the active and smart role of other life forms on Earth will help us to consider a conscious cooperation in biofabrication, hopefully respectful and sustainable.

4. The message behind a new materiality

If being connected with the natural world means to interact with it by following the rules life developed by evolution, then mimicking such rules for human purposes seems the best choice at the moment. Speaking of materials, I think there are three interesting levels to analyze from this point of view: organic materials managed in a circular economy system, materials made with living organisms and materials derived from synthetic biology. Organic (bio-based) materials, handled in a circular economy, have a very high potential in terms of environmental sustainability (e.g. regeneration of resources, disappearance of the concept of waste, closed cycles of material



Fig. 3 - InterWoven, Diana Sherer | Photo credits to Diana Scherer

flows, processes that require little energy and resources, life-friendly chemistry). Biomaterials (meaning living matter) further enhance these environmental qualities also thanks to their “interactive”, “connected” and “smart” nature. Having to frame ICS materials and processes, I wanted to give space to a co-participated design with living organisms, active and responsive to the stimuli given, intelligent for innate knowledge developed in years of evolution. Many smart materials fall also into the category of synthetic biological materials, genetically encoded to create new higher order materials (Le Feuvre and Scrutton, 2018); in this case, however, cooperation leaves room for manipulation - the reason why, despite their potential, I did not mention them in the chapter. I preferred instead to sketch what happens when design meets living matter, since I believe cooperation with other life forms is the fundamental lesson in this particular historical period: if the medium is the message, biomaterials may better underline our role on the planet. In most biodesign projects there is an evident effort made by the designer to better connect with nature; this approach underlines a certain mind elasticity, which Antonelli described as «a by-product of adaptability and acceleration» (Antonelli, 2008). Today we have the technology to accelerate our knowledge and master complexity, while the ability to interact with new disciplines, question the present and translate scientific knowledge to the public is part of the mental elasticity of biodesigners. However, this ability to adapt to new models must become a common skill: I see this discipline evolving in parallel with an economic shift, since the mechanistic model that fueled our linear economy seems to be still quite rooted in the way production is handled. If we don't solve as soon as possible this crucial bias, we risk to critically compromise the intrinsic potential of such an emergent vitalistic design.

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5. The Role of ICS Materials in Materials Libraries: Weaving Together The Fabric of the Future

by *Richard Lombard*
Matterofimportance

1. The Importance and Value of Materials Libraries

The impact of materials on our lives cannot be understated: on the grandest scale, the manner in which people utilize the resources of our planet will determine the future of its survival. On a much smaller scale, but equally important, is the single decision to use a material that is “better” for the job – be it one that is stronger, produces less material waste, or one that creates a more efficient product. One such decision can have a far-reaching effect.

- In 2010, almost 65 billion tons of raw materials were traded around the world: that number is expected to rise to more than 80 billion in the next year.
- The United States consumes between four and five billion board-feet of lumber every year, just in the manufacture of wooden pallets: that is more than 40% of the hardwood and some 15% of the softwood produced in the country.
- The U.S. also produces more than 80 million tons of raw steel every year. The Chinese steel industry is more than ten times larger than that of the United States.

As a designer, it is of critical importance to know what material options exist for the product under consideration, whether it’s a dress, a book, a chair, or a car. The blank page, representing the creativity of the designer, is only part of the picture. Materials take design off of the page and into the real world: they literally manifest our ideas. Everything that we touch and smell, and much of what we see and hear, is due to the contribution of materials. How can one design without understanding materials? To create a design first, and then attempt to source the materials that will realize it, is a recipe that often ends in frustration, compromise, and failure.

Conversely, it is impossible to understand materials without touching them. To read the word “soft” on a page, or hear the word spoken, reveals precious little about the actual material: there is furry soft, rubbery soft, silky soft – the list goes on and on. Only fingers (or, perhaps, a cheek) know the true meaning of “soft”.

It is absolutely critical to have a hands-on approach to materials in order to know how a final product will appear, feel, smell, not to mention perform. Materials are tactile and haptic – they are the real, human “interface”.

Material choices are everywhere, like the difference between a newspaper and a magazine – both simply present words on a page, but the difference between textures and weights conveys two distinct messages. Speaking of weight and texture, add both to a simple pen and any feeling of “disposability” disappears from the product.

Materials libraries, whether in academia, businesses, or public venues, offer the opportunity to truly know materials. While images can convey color and pattern, experiencing the physical material in motion shows its reaction to light – oftentimes changing said color and pattern dramatically. Far more important than that, texture comes alive, weight and drape are on full display, and rigidity and flexibility reveal themselves.

In a materials resource, it is important to see the contents as both complete solutions, ready to be utilized in the creation of product; and also as component parts to be combined to create new materials. Materials innovation has revolutionized products and structures throughout time: from stone to iron to steel, and from skins to threads to nonwovens. New material developments continuously surpass their predecessors in terms of performance, sustainability, and price. As we grapple with global sourcing and disposal issues, we need this sort of innovation even more.

2. General Structure of Materials Libraries

Materials libraries come in a variety of forms, and an equally wide variety of organizational schemes, from architectural archives of past FF&E choices to inspirational collections of the latest and greatest advances to arrive on the market. There is literally no “wrong” way to organize a materials library, as materials have virtually infinite applications, properties, and characteristics.

While it is undeniable that most material selections are application-driven, and organizing materials by their “common” application is how most users would prefer to see them, it is ultimately preferable to abandon anything having to do with application. Organization by application group, to use the

Interior Design discipline as an example, is far too limiting: many products are designed for use as flooring, but if they are durable enough for that application why could they not be used in many others?

This “end-use” orientation takes a researcher or specifier past the inherent characteristics and properties of a material, and straight to what another party has decided a material should be used for. By disassociating a material from a specific use, a resource enables critical analysis, and novel interpretations by researchers and novel uses by materials specifiers. The goal of effective material selection is to find the product that best fits the required performance and manufacturing characteristics: if those are found in a material that has never been utilized for the desired application, all the better. This is innovation.

3. Material Category-Based Organizational Systems

A preferred method, therefore, is to organize materials by their material type: Cements, Ceramics, Glasses, Metals, Natural Materials, Polymers, etc. While this is an imperfect Taxonomic Rank – all glasses are by definition “ceramics” and both Naturals and Polymers are infinitely large categories – it roughly hews to what most people expect of a breakdown of materials, and subcategories of each parent can be created to satisfy specific user groups.

The definition of “a material” is also very much in flux, and challenges many a researcher. Zinc, for instance, is an element, a commodity metal found in sheets, a key component to brass and other metal alloys, as well as featuring in advanced technologies such as zinc-silver batteries. Most materials libraries feature materials that fit somewhere between the elemental (or raw) state of the material and a product or system that contains it – in German it is known as a “halbmaterialen” or “semimaterial”: one that has been manufactured, but is still able to be worked in some manner.

4. Composites

Within any materials resource, a large number of the items found there will be composites: materials that are comprised of more than one material type. These are distinct from alloys – like brass, which is a mixture of zinc and copper – or compounds – like ABS plastic, which combines the hardness of polyacrylonitrile (A), the resilience of polybutadiene (B) and the rigidity of polystyrene (S).

One of the best known composites would be fiberglass: a glass textile encased in a polymer binder, where the textile provides a tough, multidirectional reinforcement of the polymer without adding much in the way of weight. There are myriad other examples, and more being created every day. From reinforced cements to honeycomb panels to the emerging field of bio-composites, these blends of materials present opportunities in every discipline. Composites are generally placed within the category of their largest component part: in the case of fiberglass, it would be found in the polymer section, rather than glass, as most variants contain more polymer binder than glass fabric.

5. Continuous, but not Linear, Improvement

Given the wide range of sectors that are dependent on materials research, advances come from disparate corners of industry, not to mention the world; however, many of the solutions that are developed can transition seamlessly from one industry or application to another. A broad-based materials resource cuts across silos of development, relieving the sector-based myopia that defines many research efforts, and presents materials that exhibit specific properties and meet performance goals, regardless of intended application or purpose.

The medical field is interested in developing materials that are capable of delivering treatments, both physical and emotional, that reflect a greater understanding of diseases and their impact on the human body. The transportation field is interested in developing lighter, more sustainable materials as a result of government restrictions designed to minimize the impact of fossil fuels on cities and their occupants. Ever the leader in rapid development, technology is always looking for ways to make its offerings as integrated and invisible as possible – meaning that their systems need to be part of “regular” products.

An advance in any of these fields is not necessarily limited to that specific field. A polymer developed to serve an automotive purpose could very well have the qualities and characteristics sought after for a medical application. This cross-pollination is especially useful in the realm of composites, as incremental improvements in a single element of a material can provide exponential benefits when added to a combination of materials.

6. Subcategories or Collections

With all of these “rules” it is also important to have exceptions – subcategories or “collections” – within a resource. As mentioned, this can be especially helpful in tuning a resource to a specific user group, without resorting to a default application. Textiles, for instance, are an illuminating collection as they span virtually all material groups – ceramics, metals, glasses, polymers, and naturals – and all applications. Other possible collections could be panel materials, films, reinforcement materials, textural surfaces, among many others.

7. Technology – the Boundary

What is usually NOT found in a materials library is anything that would be described as “a technology”. Technology is the realm of the Virtual World, and it would stand to figure that it would not feature in a resource dedicated to the Built World.

However, as Dutch fashion designer Pauline van Dongen said of her own research for her wearables, “I do believe that every technology is a material, and it is hard to make a separation.” This overlap, or disappearance of borders, began with the shrinking of technology; and now, miniaturization has given way to integration. No longer content to attach miniature systems to products, designers are looking for ways to make their products exist as a holistic system.

The materials that are bringing their visions to reality are ICS Materials – Interactive, Connected, and Smart Materials – and highlighting them in a materials resource would be a most valuable collection. It is in this collection that we see the greatest opportunity to leverage the power of materials, manufacturing, and technology. It is within the ICS materials realm that the fabric of the future will be created.

8. What are the properties that define ICS Materials?

As has been discussed at length in this volume, the definition of ICS Materials “encompasses materials that are: (i) able to establish a two-way exchange of information with human or non-human entities; (ii) linked to another entity or an external source, not only through the internet and digital network; (iii) able to respond contextually and reversibly to external stimuli, by changing their properties and qualities; (iv) programmable, not only

through software” (Emphasis by the author. Rognoli et al., 2016; Parisi et al., 2018).

In the broadest sense of the word, ICS materials are defined by being inherently responsive or “reactive”, to use the ICS Materials Map terminology, in a way that separates them from their static – or “inactive” brethren (Parisi et al., 2018). By this definition, and to complicate matters, there is also a desire to separate these materials from the technology that was just discussed as becoming harder and harder to separate from materials.

More often than not, these materials are responsive to humans, whether actively or passively, and they transmit either information or an action based upon that input. This “connected” aspect (or the ability to connect them) sets them apart from materials that simply respond to a change of environment.

Take wood, for instance: the material has been used by craftspeople for millennia for its ability to change form. Ancient Egyptian stonemasons inserted wooden wedges into blocks of stone, wet them, and then used the force of the expanding material to cleave the harder material in two. Coopers have counted on the expansion of their wooden staves to solidify their barrels for centuries.

A material’s response to moisture or temperature or other environmental inputs is one of the first and most foundational types of reactive ICS material. In this group, one would find materials such as shape-memory polymers and metals, UV- and thermochromic pigments (that can be added to a variety of different materials), electroluminescent materials, and – yes – there will also be natural materials like wood and paper. There would also be materials that incorporate bio-active elements capable of generating a response to an environmental stimulus.

The next most important component in an ICS resource would be those materials – materials, not mechanisms – that generate or react to energy inputs. This category would primarily be those materials that have a piezoelectric characteristic, such as ceramics and certain minerals. Their ability to transform energy into motion brought us the quartz movement and new levels of accuracy in a variety of instruments. Today, however, their ability to transform movement into energy is leading to advances in human power generation ; and they are behind a large number of advanced sensors and actuators as well.

Also found in this category would be photovoltaic materials that are currently being developed in a variety of different forms that provide proof for van Dongen’s thoughts: these technologies are being developed in ways that allow them to become true materials. From tiles to films to textiles to fibers, solar-power technology is growing ever more integral to the process of creating, rather than being something that is added later to an existing product.

Another type of “response” that is being developed for materials is the ability to heal or repair themselves. In this class of material, the material is the entire process – interactive, connected and smart – as it responds to different forms of stress or degradation through its composition. In this category, one would find predominantly materials from the polymer and cement groups, but also ceramics and metals. Utilizing a variety of inclusions, from microcapsules to (once again) bacteria, fractures in materials can initiate an automatic response that can halt or repair the damage.

9. Organizing an ICS Materials Collection

It is important to consider how this ICS collection could function, both from the specific perspective of materials development, but also from the perspective of the practice of Design.

As with all collections or subcategories, it is important to keep the organization neutral of application. In the case of ICS materials, it would make the most sense to think of them as falling into functional groups that would be appropriate to the creation of a wide variety of products – admittedly, products that will serve a “connected” or “reactive” purpose.

If we look at this construct, it is possible to see the basic groups that are required: all products begin with a substrate of some sort, inputs and outputs form the source of information and the method of communication, these are joined by connectors of some sort, and powered (generation and/or storage) in some way.

These roles, combined with a materials taxonomy, produces a useful matrix to consider their organization:

As stated before, all sectors of industry are generating material advances for their specific purposes. If that output is analyzed through the lens of ICS materials, it can be placed within a framework that becomes much more focused and useful to designers.

Tab. 1 - Organizing an ICS Materials Collection

	Substrates	Inputs/Outputs	Connectors	Power
Naturals	Textiles		Protein Nanowires	Paper Batteries
Metals	Textiles	Nitinol	Standard Wires	
Polymers	Films/Textiles	Shape Memory Polymers		Solar Threads
Ceramics		Piezoelectrics		Piezoelectrics

In each of the above categories, advances are being made across a wide range of industries: OLED lighting materials for general lighting purposes, conductive filaments produced through synthetic biology, flexible and stretchable battery technology, the list goes on and on.

If all of these materials carried the designation of an ICS material, then they could be categorized and presented in a way that pulls them from their sector of origin, and makes them more widely available to the general design community.

10. ICS Materials and the Creation of Truly Smart Materials

Notable in the above matrix is the appearance of textiles in virtually every category of material (they could also appear in the ceramics line, as they are being explored for use in battery technology).

The focus on textiles throughout this chapter is not coincidental: they are, through every aspect of their fabrication, not to mention their role in garments, ideally suited to take advantage of the ever-increasing variety of ICS materials.

It would therefore be unsurprising to read that one of the largest areas taking advantage of these materials at the time of writing is that of “wearables”. While there are numerous assessments of what a “wearable” is for the purposes of this chapter these products are loosely defined as garments that, as stand-alone pieces, are capable of sensing something – whether it is location, temperature, vital statistics – and convey that data for the purpose of storing or transmitting it, or returning a response to the user through the structure of the garment itself.

Returning to another previously discussed category of materials – composites – it is easy to see a textile-based material as a composite.

Let us start with the most basic, woven textile – literally known as Plain Weave. This fabric consists of straight fibers running in two directions, the warp and the weft, and nothing else.

This simple representation of structure is a study in modularity and substitution, not to mention connection. In the realm of ICS materials, it takes little in the way of imagination to consider replacing the “standard” fibers (wool, polyester, and the like) with conductive fibers, solar fibers, or light-emitting fibers. With the myriad points of intersection, the ability to place function, and connect it with power, is tremendously simple.

The clarity is enhanced, no doubt, by the simple, two-dimensional representation: there is no depiction of flexibility, stretch, or weight to this

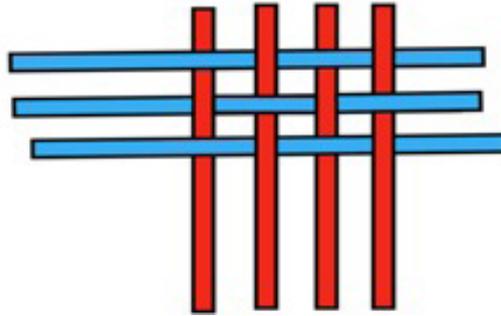


Fig. 1 - Plain Weave

structure. While this is fine for conceptualization purposes, it literally falls apart in the real world. This is where a physical materials resource truly shines compared to two-dimensional information resources.

In the real world, this textile will have to perform in ways that will challenge its structure: it will need to bend, to stretch. In most cases, it will need to endure moisture, whether from the environment or from cleaning. Beyond these objective performance criteria are the more subjective qualities of a material: is it pleasing to the eye and to the hand?

Having all ICS component parts available in a physical resource would greatly aid in the development of the next generation of products. Beyond being able to physically assess their tactile qualities, imagine if all types of conductive materials – from threads to films – were placed in the same collection. In that case, an immediate assessment could be made about the specific type of movement that the product requires and the products available (or not) to satisfy that requirement. Conversely, seeing the available form factors for power sources could change the way in which a designer approaches the cut of a garment that would include them, perhaps including them in an area not previously considered.

Another benefit of this type of collection would be to highlight and further the current trend of “materializing” technology. There are many elements of wearable technologies that must be considered as attached systems: batteries, transmitters, and the like. While these elements can be attached to a textile matrix, their fragility or form factor cannot be truly integrated into the product.

As discussed, there have been advances in the primary area affected in this way – power – with the development of photovoltaic fibers and flexi-

ble batteries. Within the context of an ICS resource, these non-conforming elements – “systems” as opposed to materials – would rapidly become the exception rather than the rule, and efforts would naturally converge on transforming them into products that could be truly integrated into the ICS taxonomy.

11. ICS – The Convergence Moment

Wearables as a category represent the ultimate convergence of the best of design, technology, and materials: and ICS materials are the focal point of this movement. The better that the design and technology community is able to understand the capabilities and limitations of these materials, the faster they will be developed and integrated into future products.

The benefits of this development and integration are many, and far surpass the integration of systems into products. As materials replace systems, there is a tremendous simplification of all aspects of product creation, from the number of component materials to the labor required to assemble them.

An additional benefit of ICS materials awareness will be a raised profile of all materials and their role in our collective future. If we are to work our way to a better future, we must all work together to utilize our resources in the most effective and efficient way possible.

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6. Intersection of Interaction Design, Crafting and Materiality: Three Case Studies of Digital Craftsmanship

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1. Introduction

Digital craftsmanship refers to making practices that combine physical with computational materials or tools, and to designing with digital technology as an expressive medium more broadly (Jacobs et al., 2016). The intersection of physical craft processes and materials with computational ones has caught the interest of researchers and design practitioners for a number of reasons. One reason is because physical craft practices have a long history and established knowledge on how to treat materials with specialized tools. And this can inform crafting with technology in contexts of digital crafting nowadays and suggest directions for future innovation when it comes to new types of materials. On the other hand, when different types of materials are combined, as for example physical ones without computational ones, such as wood with a sensor that can detect pressure, a new type of material is created. This new material has its own unique properties, including computational properties, as it can sense external stimuli. Vallgård and Redström (2007) defined *computational composites* as the combinations of computation with physical materials that together have new material properties. Computational composites have material expressions that exist in a number of states, which can be controlled or computed through algorithms or data sets. And with the development of new types of computational materials, new knowledge is needed on how to design these, and how to design with these materials.

In my work I studied how craft materials and craft practices can inform new approaches in interaction design, but also in design practices more broadly, especially concerning the development of new types of materials, and new understandings of how we can approach digital craftsmanship. In this chapter I present three case studies from my own research and design practi-

ce, at the intersection of interaction design and three distinct physical craft practices: leather, silversmith and textiles. Each of these three studies, having a different craft practice in focus, was practice-based and exploratory in nature, focusing on the materials, making processes and tangible outcomes in each case. Before I present each one separately, it is important to mention that crafts here refer to *studio crafts*, instead of other craft categories, such as DIY. In studio crafts according to Shiner (2012) and Koplos and Metcalf (2010), the designer and maker is the same person and there is a high degree of skill and experience involved. By this I want to stress that the making process in each study, as well as the way materials and making were approached was in collaboration with experienced crafts people in each craft domain.

2. First Case Study: Leather Crafting and Interaction Design

The first study I present here was at the intersection of leather crafting and interaction design (Tsaknaki *et al.*, 2014). This design exploration took place in Spring 2012, when I was working as a design assistant at Hyperwerk Institute for Post Industrial design located in Basel, in Switzerland. Throughout my involvement at the Institute, our design team was collaborating with the leather craftsman Isla Bayer. Isla was involved in our explorations on exploring the material of leather in combination with computational materials. One of our main research inquiries was focused on how to craft a touch-sensitive surface out of leather, which we integrated in the Sound Box artefact (Figure 1). This is an interactive sound table that responds to touch by playing different recorded sound files. A part of the top surface of the box is covered with leather cut in an asymmetrical pattern, and divided into five press-sensitive areas functioning as “pushbuttons”, each triggering a recorded sound file to play. The sound files were audio snippets that have been recorded during a project trip throughout which we organized design workshops with students in the Balkans.

The reason why we chose simple tactile input to trigger the audio was in order to explore how leather could be used as a material for tactile interaction, through gestures such as pushing, slight touching or stroking a leather surface. Two conductive fabric pieces were used for each pressure-sensitive area, one placed on the reverse of the leather surface and the other placed on a thick cardboard surface facing the leather, which was added just for this purpose. In order to process the sound files and control the input and output, we used Arduino and Processing open software.



Fig. 1 - The Sound Box, an interactive sound table that responds to touch by playing different recorded sound files. At the top there is a touch-sensitive surface out of leather and electronic components

From the overall process of combining leather with electronic components for making the touch-sensitive input surface of the Sound Box, and from exploring the properties of leather for this context of digital crafting, we had a number of reflections. The first one was that the thickness of the particular leather we used (4mm) offered the possibility to engrave on its surface, either with hand tools or with a laser cutter, which we used for creating visual patterns that provided information about the use of each pushbutton area. At the same time, we reflected on how this property could be used for engraving the leather for making space for placing electronic components such as cables, sensors or actuators, as part of the actual leather material, instead of attached to it.

Additionally, our experience when exhibiting the Sound Box was that leather invited people to stroke its surface and feel its texture, instead of inviting for gestures of “pushing” or “tapping” on its surface. Although this is essentially just a matter of surface, and core interactive properties still reside in the electronic behaviour, such aspects may fundamentally affect interactions and relationships with and around a designed artifact. The material affordances of stroking rather than pushing came as a surprise to us and made us adapt the interface to also allow for stroking tactile interactions. The affordance of stroking also can provide other potentially interesting use cases that would be suitable for leather, as for example to embed tactile or haptic feedback into interactive leather items.

3. Second Case Study: Silversmith Crafting and Interaction Design

The second study of digital craftsmanship was at the intersection of silversmith crafting and interaction design. It was in collaboration with the silversmith artist Emma Rapp, who is based in Stockholm, and it was initiated in 2014 (Tsaknaki *et al.*, 2017). It started as a research exploration on the design space of interactive jewellery. But at the same time it was driven by the inquiry of how to approach the design space of technological artefacts more broadly, through practices and values of craft, and in particular silversmith craft. In terms of the research approach followed and the outcomes produced, this study consists of two parts. The first part included a series of workshops and practical design explorations on how to craft electronic components, such as simple input sensors or potentiometers, made of fragile materials picked directly from nature, including dried leaves, pinecones or seashells (Fernaes *et al.*, 2014). Such types of “raw” materials were combined with copper or silver coatings, after which they acquired conductive properties (Figure 2). These handcrafted sensors were then connected to a microcontroller and were integrated in low fidelity prototypes, which were in the form of material probes that looked like jewellery items.



Fig. 2 - Simple input sensors or potentiometers made of fragile materials picked directly from nature, including dried leaves, pinecones or seashells

Through this process we reflected on how the fragility of materials could add a degree of value to a simple and very common input sensor, like a button, for example by inviting to be handled with care. But we also reflected on the impermanent aspect of materials, and thus on the impermanence and ephemerality of digital things that we use in our everyday lives, such as a mobile music speaker. Often, digital devices are easily prone to stop working, raising issues on the sustainability of materials and design practices with electronic components thrown in the garbage and causing environmental pollution.

The second part of this study included two types of artefacts that we made, which crystallize the discoveries that emerged from our collaboration in this digital crafting context. The first artefact is the Seaweed Speaker, which is a speaker designed as a necklace made from copper, leather, silver and hacked and re-used electronic components (Figure 3). It connects to a device such as a mobile phone or a laptop, and can either be worn as a necklace or placed on a surface leaving an increased openness or ambiguity in terms of where it can be placed, and accordingly, how it can be used or experienced as a device. In the case of wearing the Seaweed speaker as a necklace, the user can bring the copper seashell, where the speaker is placed, close to the ear, in order to listen to the music. It reads as a commentary on the short-lived reality of most electronic gadgets, since in contrast to most such devices, all of the electronic parts, which will likely be damaged at some point, have been made accessible in order to be replaced.



Fig. 3 - The Seaweed Speaker, a speaker designed as a necklace made from copper, leather, silver and hacked and re-used electronic components

During this digital crafting process we also designed a collection of small input controls in the form of buttons or switches, which are made from wood, copper, silver, conductive thread and Bluetooth Low Energy (BLE) modules (Figure 4). They were based on the idea of using the conductive properties of metals as a resource for interaction, in combination with the resistive properties of bare skin, and through that designing simple input controls that would be worn as jewellery, and also look like jewellery items, instead of “sensors”. Each button can communicate wirelessly with a remote device, such as a mobile phone or a laptop, and can be programmed through the Processing software platform. We imagined such buttons to be worn as bracelets or brooches and to be programmed in order to control various functions on a user’s remote device, ranging from answering a phone call to changing the background colour of a mobile screen, for example.

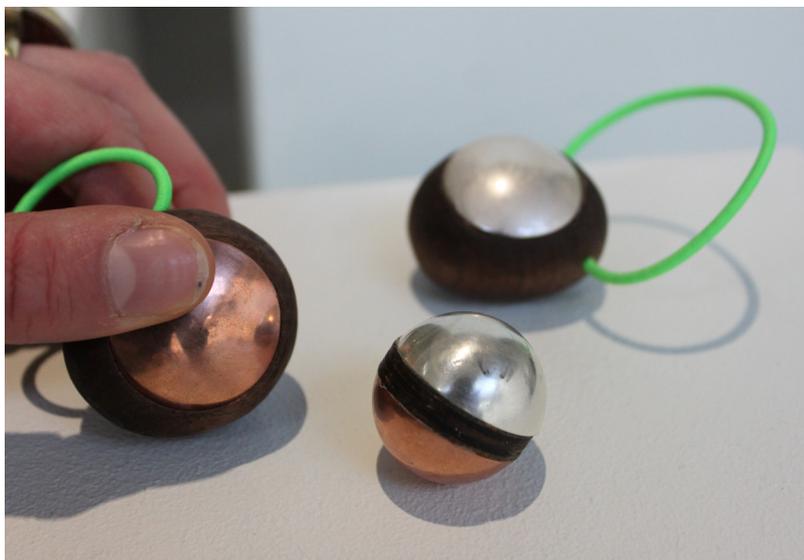


Fig. 4 - A collection of small input controls in the form of buttons or switches, which are made from wood, copper, silver, conductive thread and Bluetooth Low Energy (BLE) modules

4. Third Case Study: Textile Crafting and Interaction Design

The third digital crafting study was at the intersection of interaction design and textile crafting and it was initiated in 2014 at KTH Royal Institute of Technology, located in Stockholm, in Sweden. It was initiated by a multidisciplinary research group with an expertise in interaction design, textile design and sound and music computing. For about one year we engaged in weekly design work at the intersection of these domains, aiming to explore possible ways of sonifying body gestures and movements through a garment. During this study, an exploratory and research through design approach was followed, starting from the available material space at the intersection of crafts, software, sound programming and computational materials (Tsaknaki and Elblaus, 2019).

After a series of prototypes and design iterations the main design research artefact was the Nebula interactive garment (Figure 5). This garment is a wireless studded cloak that reacts to the movements of the wearer and responds with an ethereal soundscape. The opening and closing of the folds and the

many studs that clash, apart from being the main visual element of the Nebula garment, are also the mechanics by which the garment is made interactive. The large folds of fabric that follow the movements of the wearer in a lagging, pendulum-like fashion are translated into sounds, in real time, through the studs. Some of the clusters of metallic studs in the front are connected with copper thread to the analogue inputs of an x-OSC I/O circuit board, and some to the positive voltage output. The transmitted OSC-messages from the x-OSC board are received on a laptop by custom software written in the SuperCollider programming language.



Fig. 5 - The Nebula interactive garment, a wireless studded cloak that reacts to the movements of the wearer and responds with an ethereal soundscape

To sense the folding and flowing of the fabric in motion we explored the potential of studs to be used as a sensing material, due to their conductive properties. This led to us using a combination of metallic studs and copper thread as the central component of the activity sensing, which was a new type of computational composite material used in this context, merging exposed functionality and aesthetics into one element. The decision to use metallic

studs for both the computational sensing as well as a prominent visual component allowed the integration of the different material layers through a focus on interaction. The design process was guided by the urge to explore implicit modes of interaction, including subtle movements, or shifting of body weight in wearable contexts, from an open-ended material perspective.

Reflecting on the overall design process and on the material qualities of the Nebula, we observed that the design process led to a garment with distinctly heavy and embracing qualities, which informed the design of the soundscape and consequently, the overall interactive experience it offers. In addition to that, the active choice of studs as the main interactive and at the same time visual component of the garment, allowed for a seamless bridging of interaction and experiential qualities. Finally, in regard to the designing of the sound in this wearable context, we used the physical properties of the garment as a metaphor for crafting the audio modality.

5. Reflections and Future Research Directions

We are already engaging with new types of smart interactive materials in our practices, and this space will probably continue to grow in the future. So what are important topics to take into account for future developments in this domain? Below I will briefly present three topics that demand careful attention and consideration, and which were highlighted in the digital craft studies presented above.

Raising Issues on Sustainability

Collaborating with craftspeople and combining physical crafts and materials with computational ones raised issues on sustainability. The three studies made me reflect on the *potential of craft to contribute to creating value*, when developing new computational composite materials or when making computational artefacts. Sustainability in these digital crafting studies was seen from a perspective of how we can use the craft values as an action potential in designing interactive artifacts and new computational materials - that are sustainable because they are valuable or precious for people owning and interacting with them.

We observed that craftspeople use materials resourcefully while crafting, aiming not to waste material. This was present both when making the touch-sensitive leather surface for the Sound Box but also when working to-

gether with the silversmith craftswoman. Additionally, craft materials and craft practices raised the question of how crafting new smart materials and computational artefacts would support practices of mending and repair over time. Craft is built on the premises of taking into account and accepting the impermanent nature of physical materials, and even expecting the fact that materials and things degrade over time. Inspired by craft, we questioned how computational things could support similar practices, which we explored in the second digital crafting study. We took the notions of mending and repair to the extreme and we designed all the cases hosting electronic components to be able to close and open easily providing access to the electronics, and thus supporting practices of repair over time. But moving beyond electronic components to think of actual smart materials with possibilities of sensing and actuation embedded on those, sustainability and value should be important issues to consider.

On a broader scale, from a perspective of sustainable design, if we accept that most interactive products cannot be expected to last forever, it is very relevant to start considering further use of physical materials that might have a shorter life cycle, that are biodegradable, or possible to produce using environmentally friendly processes. Similarly, when developing new computational composite materials it is important to consider how they can be disassembled in order to recycle their physical and digital components. But also how they can be crafted in a way that would create value, for example by contributing to rich sensory experiences in interaction, and thus to have the potential to be kept for longer.

Expressive and Sensual Materials

Craft materials, such as leather or wood, most often evoke rich sensory experiences, which range from tactile to visual, auditory and even olfactory. When making new types of computational materials it is important to also consider the felt and sensual experiences that such materials would evoke in interaction, beyond only considering their functionality, such as their range of connectivity. How will a new type of material invite someone to interact with it, based on its properties? Can we develop new materials that will have expressive and sensual qualities and contribute to rich engagements with technology? Material sensuality could be understood as expanding on a spectrum of mainly pleasurable experiences arising through our senses, including enjoyment, satisfaction or pleasure. Additionally, it can be considered as being related to previous research on somaesthetics in interaction de-

sign (Höök, 2018). According to Höök (2018), the movements, experiences and sensual appreciations of our own somas, meaning a holistic perspective of our body and mind, will be changed, extended and molded through their interactions with a system, and through the aesthetic potential of the sociodigital materials that we interact with.

As articulated in the first study focused on leather, people felt inclined to stroke the touch-sensitive input leather surface instead of pushing on its surface. In the third digital crafting study that resulted in the Nebula interactive garment, material sensuality was central in our approach to designing the interaction with the garment. The sound was closely linked to the subtle contact created among the metallic studs, in combination with the properties of the garment, being enclosing and heavy. When wearing it and interacting with it, the wearer can “feel” how the soundscape is created through the clashes of studs. Finally, the material sensuality evoked when using the Seaweed Speaker was on a level of the acoustics of sound coming out of the speaker. Since the speaker was hosted inside a copper shape that was given the form of a seashell, the sound coming out of it was deep and distant, and consequently gave particular qualities to the experience of listening to the music from this artefact.

Material sensuality should not be understood as a “static” material quality, that either exists or not, especially since it is related to the passage of time, to the impermanence of materials and to the evolution of technology. One way of designing for expressive and sensual experiences through smart materials, could be to take into account this impermanent aspect manifested as patina, for example, on a level of physical and computational materials. And through that to design for material sensuality in interaction that would evolve and adapt to new circumstances, such as user needs or preferences, by allowing for a dynamic inscription of patina from a user perspective.

From Material Making to Material Programming

Apart from exploring the design space of *making* new material composites with combinations of physical and computational materials, it is also important to consider the practice of *programming* such materials. In a research project I was involved in, a few years ago called *Material Programming* (Vallgård et al., 2017), we proposed a speculative idea of how an interaction designer would better explore the dynamics of the materials at hand and be able to compose more sophisticated and complex temporal forms, when programming smart and connected material composites. In the same work, we

developed a set of hand-manipulated digital tools and envisioned how they could be used to program smart materials, similar to specialized tools used in physical craft practices. As such, material programming as a practice would blur the boundaries between programming and crafting new smart computational materials.

With the recent developments of Interactive Machine Learning (IML) technologies, there are new challenges and opportunities emerging for the research space of programming computational composite materials. One direction of interest would be to explore the use of interactive machine learning tools for supporting ideation and prototyping of interactions with smart materials using bodily data, and thus offering a tight coupling between sensing our bodies and actuating on smart materials.

6. Conclusion

In this chapter I presented three digital crafting studies that took place in collaboration with studio crafts people in the domains of leather, silversmith and textile crafting. I presented the design research artefacts that emerged from each study, focusing on the combinations of materials used that resulted in new computational composites. I ended this chapter with a brief discussion focusing on three topics that emerged from my studies, and which would be important to consider in future work on designing with smart materials. The first one is about considering sustainable practices, the second is about designing new materials that would have expressive and sensual properties, and the third is about the design space of programming smart materials. Finally, it is important that research in new materials and design practices should be focused on inscribing subtle and hidden qualities to physical as well as computational things; qualities that invite us to touch, smell, interact, admire and acquire those, due to a complex but rich entanglement of elements that make them materials, and consequently artefacts, that evoke feelings and memories.

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7. Unlocking the Potentials of Underdeveloped Smart Material Composites

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1. Introduction

Ever since the establishment of materials science, the discovery and development of new materials have largely become a scientific activity. Materials testing and mathematical definitions of their properties, such as strength and roughness, provided precise numerical data for the design and engineering of material applications. However, the dominance of science in determining the direction of materials development has also led to undesirable consequences (Miodownik, 2007), one of which is prioritizing technical performance of materials over their non-technical aspects, including their sociocultural meanings (Manzini, 1989), *sensorial-expressive* (Rognoli, Salvia, & Levi, 2004) and *performative* qualities (Giaccardi, & Karana, 2015) elicited when we interact with materials in a specific context of use (Karana, 2009).

Over the last decades, we see increasing collaborations between materials science, art, and design communities, to account for an understanding of this *experiential* side of materials next to their technical performance (e.g., Collette, 2017; Lefteri, 2012; Montalti, 2017; Nimkulrat, 2009). These so-called ‘upstream’ collaborative projects strive for changing the dominant schemes of *design being downstream of technology* (Bergström et al., 2010), by involving designers in the early stages of materials development (Mani, Cutcliffe, Penã, & Andersen, 2014; Nathan et al., 2012).

In this Chapter, we share our experience as design researchers in one of these collaborative projects: Light.Touch.Matters (LTM) (2013-2017), which was an EU funded project that put into practice such upstream collaborations between designers and materials scientists. The LTM project focused on the development of a particular composition of two smart materials,

namely organic light-emitting diodes (OLED) and piezoelectric polymers, i.e., the LTM materials. At the early stages of their development, the LTM materials were communicated to designers through descriptions of their physical and functional characteristics (e.g., pressure sensitive) and schematic representations (see Figure 1).

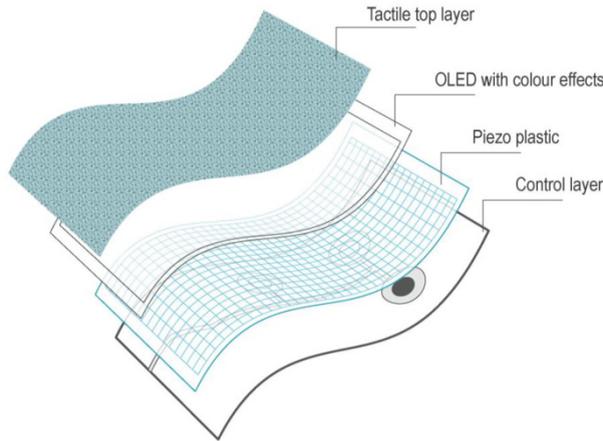


Fig. 1 - A schematic representation of the components constituting the LTM materials (source: Miodownik, & Tempelman, 2014)

The LTM project implemented the steps of a predetermined methodology in organizing the interfaces between designers and materials scientists. Departing from *scenarios of meaning* and *new experiences*, the designers and material scientists worked in parallel and had occasional workshops, where they came together and exchanged information and representations of the “underdeveloped” material and the proposed product applications.

We coined the term ‘*Underdeveloped Smart Material Composites*’ (USMCs) to make an explicit reference to unique aspects of the LTM materials, namely their underdeveloped state and their dynamic qualities. This term helped us to organize our research beyond the specific case of the LTM materials. It allowed us to look at a broader range of smart material composites that may serve as a departure point in other material driven design processes. Being interested in USMCs and designers’ involvement in designing and further developing these composites, the main research question we tackled was:

How do designers understand, explore, and unlock the potentials of underdeveloped smart material composites?

In this Chapter, after addressing the challenges of Designing with USMCs, we introduce our research approach and summarize the main implications and findings of our research¹ (Barati, 2019).

2. Challenges of Designing with USMCs

Smart materials are broadly defined as a group of different materials of which their intrinsic properties change, reversibly, in response to particular stimuli, including mechanical strain, changes in temperature or electromagnetic field (e.g., Addington, & Schodek, 2005). In the case of LTM materials, a pressure/deformation sensing component, i.e., piezoelectric polymer, and a light-giving component, i.e., OLED, were envisioned to constitute a single material composite. In line with the incentives for developing thin and integrated composites of smart materials (see McEvoy, & Correll, 2015), these flexible and formable composites aimed to provide alternative solutions to the current flat interface technologies (cf. Coelho et al., 2009; Nijholt, Giusti, Minuto, & Marti, 2012).

Considering the material composition as underdeveloped gives designers higher degrees of freedom concerning the unspecified material properties and experiential qualities. By building tangible representations of the underdeveloped material, designers can contribute to the discussions of the experience and impacts of the smart material, prior to its actual development (Bergström et al., 2010). In addition, the dynamic and responsive properties of smart materials can open up new design spaces, blurring the conceptual boundaries between physical and digital, matter and information, structure and membrane (e.g., Addington, & Schodek, 2005; Coelho, & Zigelbaum, 2011).

On the other hand, investigating the potentials of novel smart materials and designing with them is also known to be a challenge for designers (Schröpfer, Viray, & Carpenter, 2011). Difficulties can stem from the conditions of early material development, such as having no material sample to work with (Bergström et al., 2010) and having no design precedents or body

¹ This chapter presents parts of the 1st author's doctoral thesis at Delft University of Technology (see Barati, 2019).

of knowledge regarding the manufacturing and user experience of the new material. Additional technical and methodological challenges are expected when incorporating smart materials in the design process (Bergström et al., 2010; Bohnenberger, 2013). The design approaches that involve materials only in later stages of the design process are not apt for smart materials (e.g., Addington, & Schodek, 2005; Bergström et al., 2010; Bohnenberger, 2013). As functional materials that can sense and respond to their environment, smart materials and designing with them demand an understanding of the dynamic relations between material, environment, and design rather early on in the design process (Addington, & Schodek, 2005; Bohnenberger, 2013).

In his doctoral thesis, Bohnenberger (2013) motivates new design tools to overcome the difficulties of designing with smart materials, in relation to three main topics: *material thinking*, *material representation*, and *interdisciplinary communication*. The first topic concerns the differences between how materials scientists and designers think about and act upon materials. It is mostly accepted that materials science acts bottom-up, operating at the nano- or micro-level to change the material structure, whereas designers tend to operate at the product-scale and search for suitable materials, i.e., product-oriented approaches (Ashby, & Johnson, 2002). In other words, rather than in the material behavior itself, which falls in the interest and expertise area of materials scientists, designers' main interest is in already specified characteristics and existing applications (Addington, 2006). The second topic touches upon a limitation of the static modes of representing materials in terms of their physical properties and functionality. The existing tools and methods, such as visual collage and verbal descriptions are insufficient to capture and communicate the complexity of materials behavior that is dynamic and reactive to its context (Bergström et al., 2010). Material representation becomes a central issue when introducing USMCs to designers in the absence of the actual materials. The final topic takes notice of the distributed knowledge between the fields of design, engineering, and materials science and a need for interdisciplinary communication and exchange. The differences and discrepancies between foci of interest, means of communication and vocabularies, and the knowledge gaps can hamper effective and fluent communication between designers and materials scientists (Ashby, & Johnson, 2002).

More recently, there has been an emerging body of research, aiming to understand and mitigate the challenges of upstream collaborative projects. For instance, the studies of Wilkes et al. (2016) and Hornbuckle (2018) highlight the multidisciplinary challenges of collaboration for materials deve-

lopment. To facilitate communication and knowledge transfer between designers and materials scientists, respectively, they emphasize the mediating role of isomorphic material samples, which take a systematic approach to exploring the relationship between the technical properties of materials and the sensorial experiences of their sound, taste, and feel (Wilkes et al., 2016); and material liaisons, who are familiar with both worlds of design and materials science (Hornbuckle, 2018). Taking place in the context of projects with stakeholders distributed across Europe, who gathered up every 2-3 months in a workshop setting, the two studies propose solutions for facilitating interdisciplinary communication of materials.

Other researchers have looked into alternative means of representing smart materials and digital technologies that involve dynamic properties. Sundström et al. (2011), for instance, emphasize the limitations of “black-boxing” technologies when representing them to designers, favoring approaches that expose the technologies’ dynamic properties in supporting the collaborative exploration of their design possibilities. Their proposed approach, referred to as *inspirational bits*, is a range of small games or investigations specifically designed to engage all the members of the development team in getting to know the working principles of a technology and its peculiar properties and limitations. Rather than aiming to achieve a final design with the technology, the focus of investigation is to open up to anything different and/or unexpected and inspirational in that technology. Directly related to smart materials, Bohnenberger (2013) shows the relevance of dynamic computational models and simulation tools, developed based on early physical engagement with smart material properties. According to his practice-led studies, a real-time simulation of the material’s behavior as a function of its specified structural and environmental parameters can foster a closer discourse between designers and materials experts (Bohnenberger, 2013).

This overview indicates that exploring the potentials of smart materials might be hampered not only by the technical complexities of their dynamic properties and inappropriateness of the product-oriented design approaches, but also by how the transactions between designers and materials scientists are structured, i.e., the organizational structure of the collaborative project.

3. Research Approach

To address the main research question, we initiated an exploratory study into the design processes that departed from the LTM materials (Barati, Karana, & Hekkert, in press). This included a number of student design projects

that departed from the same introduction to the LTM material and the same design brief professional designers had been provided with. Our findings from the *interview studies* with design professionals and observations through the student design cases showed that understanding the experiential qualities of these materials, in particular their dynamic (e.g., changes of light intensity over time) and performative (e.g., actions for activating the light) qualities, necessary for unlocking their design potentials, was challenging. The difficulty rose mainly due to a lack of direct experience with the underdeveloped composite or otherwise tangible representations of it, which could let the development team directly experience the dynamic and performative qualities.

In parallel, we initiated *material driven design cases* to investigate how materiality of a USMC influenced the creative process, particularly the discovery of novel potentials. Material driven design refers to non-linear, non-standard design and material practices (Kolarevic & Klinger, 2008) that depart from the material and follow its specificities, such as the properties and behavior for a design outcome that is informed by the material itself (Bohnenberger, 2013; Karana, Barati, Rognoli, & Zeeuw van der Laan, 2015). In our research, we supported our design students with a systemic, step-wise design method, i.e., Material Driven Design (MDD) method (Karana et al., 2015), with an explicit focus on designing for material experiences. The method motivates an understanding of materials as structural and functional building blocks of products, as active collaborators in unfolding our experiences with and through them (Giaccardi, & Karana, 2015). By encouraging “a sensitivity to flows and transformations of materials” (Ingold, 2009) through materials tinkering and processing, and a simultaneous understanding of the technical and experiential qualities of materials in defining their potentials, the method opens up novel opportunities for further development of materials.

In order to facilitate the exploration and communication of the LTM materials’ dynamic and performative qualities, we proposed a two-fold solution. The solution incorporated (1) *a smart material demonstrator* (Figure 2) that clearly communicates a gap in experience prototyping at the intersection of performable structure and responsive surface lighting; and (2) *a hybrid sketching tool* (Figure 3) that digitally augments the surface of physical objects with computer-generated dynamic behaviors.

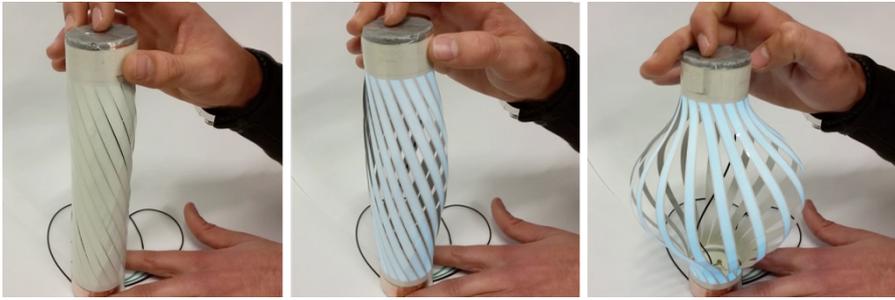


Fig. 2 - The demonstrator features a dimming effect corresponding to structural deformation



Fig. 3 - Using the input device to control the dynamic behavior of light (left) and the appearance of the real-time Chroma-key effect on the screen (right)

The proposed solution illustrated the importance of “*experience prototyping*” in the early stages of the co-development of the USMCs to understand and communicate their performative qualities. A smart material demonstrator was created *using electroluminescent (EL) materials to support a direct experience*, showing a performable structure that gradually dimmed/illuminated in response to the user’s action of twisting. The idea behind the sketching tool was to let the development team subjectively experience dynamic surface lighting of a performable structure unfolding over time and in response to their actions. The *Chroma key technique* was used to over-impose the dynamic light patterns in live-stream videos of the interaction with the physical samples and mockups. The interviews with the LTM designers who had tried the first version of the tool indicated that such a sketching tool could have considerably improved the interdisciplinary communication of the dynamic qualities of the LTM materials. Three stages of the development

process were considered of special importance: (1) when introducing these materials to the designers, (2) when representing the early application ideas to the material scientists, and (3) when further developing the concepts within the design team.

The unprocessed electroluminescent (EL) materials, which were used for creating the demonstrator, provided a relevant starting point for the material driven design process. Not only the EL materials resembled the thin-film OLED component of the LTM materials, but we were also able to provide the design students with in-house equipment and expertise needed for fabricating EL material samples.

In a case study (Barati, Karana, Jansen, & Claus, in press), we reported on a designer’s journey that departed from the unprocessed EL materials. The activities and decisions made throughout the material driven design process were recorded. Unlike the design processes with the LTM materials, in which the designers had indirect access to the USMC through material information and physical representations, the design student was instructed to actively participate in material making and processing. The case study showed that a designer’s hands-on approach together with his interest in the experiential aspects of the EL materials, concerning the aesthetic experience and performative character of the material samples, unfolded new action possibilities and development trajectories. The designer’s contribution to materials development in this material driven design case clearly reached beyond finding meaningful product offerings. Throughout the process, the designer discovered new ways to alter the performative character of the EL material samples, which were not “given” or known prior to the design process (Figure 4).



Fig. 4 - Using water as a replacement for the conductive layer to create samples that encourage new interaction modes

4. Discussion

Acknowledging Designer's Shifting Role from Passive Recipient to Active Explorer

Our research approach and findings challenge the dominant role and contribution of designers in upstream materials development projects to 'come up' with application ideas. The organizational structure that constraints the designers to top-down approaches in understanding the material potentials, based on descriptions of the USMC and the static representation techniques (e.g., schematic structure) can compromise designers' creative contribution that may well go beyond product application offerings.

The emerging design practices at the intersection of design, materials science, biology, arts, and crafts suggest that designers' creativity does not stay within the application potentials of novel materials. Over the past two decades, we have been witnessing a growing number of 'experimentalists' and 'makers' among artists, designers, architects, and engineers with a focal interest in materials fabrication (see Bohnenberger, 2013; Karana et al., 2015; Kolarevic, & Klinger, 2008; Kretzer, 2017; Oxman, 2010). Fundamental to this ongoing development is a new attitude towards achieving design intent through interrogating materiality (Kolarevic, & Klinger, 2008), a return to 'making'; a shift of paradigm towards material driven design approaches (Oxman, 2010). In identifying designers' creative contribution to materials development and exploring how they unlock the undiscovered potentials of USMCs, it is critical to look into material driven design situations that involve transdisciplinary material making/developing activities.

Towards Equal Partnership in Collaborative Materials Development

The comparison between the LTM project and material driven design situations urges for equal partnerships of designers and materials scientists in collaborative materials development projects. The project organization and methodology should enable designers' active participation in discovering and defining material potentials and boundaries. Our material driven design cases and many similar cases contradict the expected role of designers to be material/technology "applicators" and rather promote them as active makers of the new material. Researchers have previously touched upon the limitation

of relying merely on user-centered approaches in understanding digital materials, arguing that these approaches should not distract the multidisciplinary development team from collaboratively exploring their potentials and boundaries (cf. Sundström et al., 2011).

Reducing designers' creative role in collaborative materials development to 'coming up' with application ideas is a logical consequence of creativity being understood as "in the designer's mind". Mainstream creativity literature reinforces that creativity is closely associated with divergent thinking (Guilford, 1950) and having an associative mind (Mednick, 1962), evident in activities such as idea generation. However, recent creativity theories, such as the work of Glăveanu (2012, 2014, 2015), try to understand creativity from a socio-cultural and developmental psychology perspective, as an action outside of the designer's mind, in interaction with the material, the social situation, and over time. The social dimension of creativity (Glăveanu, 2015) asks to look into the interrelation between designers and material scientists in collaborative projects, not only in terms of multidisciplinary communication and transferring knowledge, but also with respect to their expected roles, autonomy and authority (e.g., the ownership of the project), and the impacts these may have on collectively exploring the novel material affordances.

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Part Two
Discovering ICS Materials:
Framing the Phenomenon

1. ICS Materiality: the phenomenon of interactive, connected, and smart materials as enablers of new materials experiences

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1. Living in an interactive, connected and smart world

In many areas of our private and social life, digital technologies are emerging with increasing strength and conviction. In the entrepreneurial and productive spheres, companies invest in digitalization following the guidelines of the new policies and riding the ever-increasing wave of financing aimed at new digital technologies. In front of such a promising context and an increasingly insistent demand, even the designers are invited to shape this umpteenth technological revolution. They have the responsibility to interpret this ambition for the miniaturization of information technologies and the diffusion of interdisciplinary environments that fuel cross-fertilization and the merging of previously isolated and distinctive practices. The ongoing direction we are increasingly witnessing is that the artefacts we use and wear in our everyday life are becoming more and more embedded with smartness. Smartness is the quality of an object to adapt to circumstances by reacting to different stimuli. While, at the level of designing interactive objects and systems for tangible interfaces, research and practice are already advanced, instead, at the level of the development and application of materials enabling smartness for purposeful and meaningful interactions, there are still significant progress to be done.

Indeed, the actuation of smartness will potentially evolve by instilling it in the matter itself thanks to miniaturization of technologies, instead then integrating it with interactive technologies. This will allow for seamless results avoiding the obtrusive presence of technology in the users' everyday life and promoting a more natural and sustainable approach to interactive objects, potentially enhancing novel and positive experiences. New materials with interactive and connective qualities that can be programmable and incorporated into intelligent systems are required to achieve this fully embedded degree of smartness.

As the products of our current time are and will increasingly be interactive and smart, designers and labs have also begun to work on developing connected and interactive materials, thanks to their hybridization with technology (Pandey, 2018). This reinforces an ongoing shift in the paradigm of relationship and agency between the designers, the design, and the materials: from being passive entities to choose from, materials have become active elements participating entirely in the design process, becoming the object of the design themselves. Indeed, these materials become able to sense and to communicate information, by performing behaviours by moving, changing colours, or by lighting up, and many other interactions. Thanks to this new agency and dynamism, starting from the shelves of the material library, where conventionally the samples are only stocked and catalogued, the material samples have gone on to be considered the main protagonists of the design process and the experimentation driven by design. This complex phenomenon revolutionizing materiality can be defined under the umbrella of Interactive Connected Smart (ICS) Materials and their implications in the design field.

In this chapter, we will propose a definition of Interactive Connected Smart (ICS) Materials, and we will identify the main elements constituting them. Finally, we will present the main experiences enabled and implied by these materials.

To define ICS Materials, we based on the results of the FARB 2015 project promoted and funded by the Design Department of the Politecnico di Milano (www.icsmaterials.polimi.it). In this extend, we consider all the relevant outcomes and findings from research and teaching experiences carried out by the authors.

2. What are ICS Materials

The concept of Interactive Connected Smart (ICS) Materials encompasses a broad range of materials that are defined by some of the following characteristics (Rognoli, Ferrara and Arquilla, 2016; Ferrara et al., 2018): be able to establish a two-way exchange of information with human or non-human entities; be able to respond simultaneously and reversibly to external stimuli, by changing their properties and qualities, for example - but not limited to - colour-changing, light-emitting, shape-shifting behaviours; be linked to an external or integrated source of energy and communicating with a source of information, for example - but not limited to - through cables or digital networks; be programmable, for example - but not limited to - through software.

To have these interactive, connective and smart capabilities, ICS Materials are modelled as complex systems made by all or some of the following interdependent “building blocks” or “layers” (Parisi, 2020).

Conventional materials include materials such as plastic, paper and textiles that can be used as a support and structure in the system. Besides some mechanical and chemical interactions, such as performing flexibility and ageing, they do not perform dynamic and reversible behaviours. Therefore, they are latent materials with no evident interaction.

Smart materials are the ones that have changeable properties. They can reversibly change some features like shape, colour or light-emission in response to external chemical or physical influence, for example, light, temperature, electric or magnetic field, pressure and mechanical stress, chemical elements and compounds. The quality of the behaviour and the way these materials perform is programmable, i.e., they are engineered to respond in a predetermined way to the stimulus in a predetermined range. Frequent examples of these materials are shape-memory alloys (e.g., Nitinol, Flexinol, Muscle Wires), colour-changing (e.g., thermochromic, photochromic, electrochromic, halochromic pigments, inks and coatings), light-emitting (e.g., fluorescent, phosphorescent, and electroluminescent materials) materials (Addington and Schodek, 2004; Ritter, 2006; Ferrara and Bengisu, 2013; 2018)

Passive technologies include embedded sensing, such as sound, touch, and proximity sensors. Also, conductive materials can be used as sensing systems. They are mainly graphite, active carbon, and silver, and can be found in the shape of conductive fibres, threads, printed circuits, paints, and coating.

Active technologies include actuating technologies, e.g., LEDs, buzzers, or vibration actuators. Both passive and active technologies are connected with external or embedded computing technologies. Arduino or Flora boards are commonly used in prototype and experimental level applications.

Sources of energy can be external via wires and plugs or integrated with traditional batteries. Embeddable power supplies and harvesting systems can be alternative technologies and materials like flexible batteries, advanced solar panel systems, dynamo or electricity-generating materials, such as piezoelectric smart ceramics and polymers: on applying mechanical stress to piezoelectric materials, they generate an electric current.

Interconnection between components is supported and enabled by additional materials that can be found in the system wires, i.e. or conductive materials that can substitute traditional wires and cables.

If we combine one or more of these components - by layering or embedding -, we could achieve systems with different degrees of interaction, as

presented in (Parisi et al., 2018 a) and in the next chapter (see chapter 2.2). Although having interesting functional implications, for example, tracking and adapting functions in different sectors and scenarios - which are described in the section III of this book -, ICS Materials present both material qualities and dynamic behaviours, enabling and implying complex and novel experiences that are worthy of understanding and enhancing. The lenses of the expressive-sensorial qualities and Materials experience are essential in the understanding and development of these materials, putting the sensory, emotional, and cultural relationships with the users in a pivotal point.

3. The lens of Materials Experience and expressive-sensorial qualities of materials

Nowadays, investigation on materials for design considers the expressive-sensorial and experiential qualities of artefacts as central, besides the technical properties of materials and their manufacturing characteristics (Ashby and Johnson, 2002; Rognoli, 2004; Rognoli, 2010; Karana, Hekkert and Kandachar, 2008 a; Veelaert et al., 2020). It is now acknowledged that materials require to have qualities that go beyond the fulfilling of practical and functional needs. They are qualitative aesthetic, expressive and sensorial characteristics eliciting intangible qualities related to cultural and personal meanings, perception, emotions and affectivity, that captivate the appreciation and acceptance by users and that affect the experience of an artefact beyond its functionality.

Rognoli, during her PhD research (2004), defined the sensorial, subjective, and qualitative profile of materials as their expressive-sensorial dimension. From this standpoint, materials have a role in characterising artefacts' perception, interpretation, and emotion, via their qualities. Examples of qualities are texture (smooth/rough), touch qualities (warm/cold, soft/hard, sliding/no sliding, light/heavy), brilliancy (glossy/matte), transparency (transparent/translucent/opaque). Designers are supported by flexible tools and methods for understanding, describing, and designing the material qualities of an object. Some relevant examples are the Expressive-Sensorial Atlas (Rognoli, 2010) mainly used in education (Pedgley et al., 2015), and the tools and methods used in the contemporary practice of Colours, Materials and Finishes (CMF) Design (Becerra, 2016). Therefore, designers can intentionally integrate, transfer or reinforce in an artefact some specifically "designed" qualities or references that all together trigger the desired material experience.

The concept of materials experience - introduced by Elvin Karana (Karana et al., 2008 a) and then further investigated, developed and extended (Karana, Pedgley et al., 2015; Giaccardi and Karana, 2015) - is defined as the experiences that people have with, and through, the materials embedded in a product. It describes a holistic view of materials for design, emphasising the role of materials as simultaneously technical and experiential. Taking materials experience as an entry point, it is possible to understand and describe how people experience materials and how physical, biological, social, and cultural conditions constitute these experiences. Furthermore, it is possible to inspire innovative material applications as well as new materials and design research trajectories. This definition acknowledges and emphasises that, through shaping what we feel and think, materials have the agency to foster meaningful experiences.

The Materials Experience is modelled according to four experiential layers affecting each other (Karana et al., 2014; Karana et al., 2015):

1. the sensorial level (i.e., the aesthetics of materials) is the experience that originates from perceiving and noticing material sensorial information by senses. The sensorial experience of a material is related to sensorial information, such as softness, warmth, smoothness, sound, weight, stickiness and so forth. The expressive-sensorial characterization of materials determines this level.
2. the interpretative level (i.e., meanings of materials) is related to the meanings evoked by the material and are associated to abstract concepts, e.g., materials are modern, natural, professional, cosy, etc. (Karana, Hekkert and Kandachar, 2008 b; 2010)
3. the affective level (i.e., emotions) is connected to how the materials make us feel and which emotions are elicited, e.g., feeling surprised, bored, excited, etc.
4. the performative level (Giaccardi and Karana, 2015) is related to the active role of materials on shaping our physical actions, ways of doing and practice. The materials can suggest us to interact in a precise manner, e.g., to scratch, finger, squeeze, etc.

It is evident now that scholars in the field of materials for design had then stressed the central role of materials in shaping meanings, sensorial and emotional interactions, highlighting how the right choice for material and process affects the user-product relationship, and often contributes to give to products the features that are mediators of the quality of the interaction itself (Wiberg and Robles, 2010; Rognoli et al., 2011). Instead, the Human-Computer Interaction (HCI) and Tangible Embedded Interaction (TEI) community still considered only the functional properties of materials, and they did not believe their power as signifiers (Regier, 2007; Fernaeus and Sundström, 2012; Hornecker, 2010). We have to wait until the formalisation

of the “material turn” (Robles and Wiberg, 2010) - and consequently “material move” (Fernaesus and Sundström, 2012) and “material lens” (Wiberg, 2014) - for HCI to put a particular emphasis on the methodological importance of closeness to the materials-at-hand and on underlining the importance of actively working with concrete materials even in the HCI domain. It was established that thanks to the material interaction, it is possible to activate “a knowledge-generating process inseparably intertwined with, and enabled by, a material discovery process” (Wiberg, 2014). Wiberg stated that materiality could be a framework to understand computational artefacts and their social impacts, which describe how the interactivity of digital computing manifests itself in a material form. The key feature of this notion is the dynamic relationship between people and interactive systems concerning the materiality of artefacts (Wiberg, 2018). Finally, HCI research shifted its attention from the materiality of information to materiality of interaction in the context of material-centred interaction design (Zhong et al., 2020). Therefore, the community around HCI and TEI has started to look at interaction and experience with materials as a complement to interaction with digital technology, bringing in novel computational properties of temporality, reversibility, computed causality, and connectivity (Vallgård and Sokoler, 2010), and identifying aesthetic dimensions, namely pleasant, interesting, comfortable, playful, relaxing, special, and surprising (Petrelli et al., 2016).

4. Exploring ICS Materials as enablers of novel materials experiences: methods and results.

ICS Material may be enablers of novel and meaningful materials experience, as a combination of the expressive-sensorial characteristics, meanings, emotions, and actions elicited by their material components and interactive behaviours. In the last years, the authors of this chapter carried out workshops with students, professionals and colleagues to collect findings on the main experiential patterns emerging from the observation and interaction with these materials using samples (Parisi, Holzbach and Rognoli, 2021), developing prototypes and demonstrators (Parisi et al., 2021; Parisi, Holzbach and Rognoli, 2020), or observing pictures of best examples and visualized concepts (Parisi et al., 2019 a; 2019 b). Data were collected employing questionnaires and in-situ observation doing rapid ethnography and integrated with data resulted from the observation of best examples through pictures, videos and descriptions (Parisi et al., 2018 a; Parisi et al., 2018 b; Parisi and Shetty, 2020).

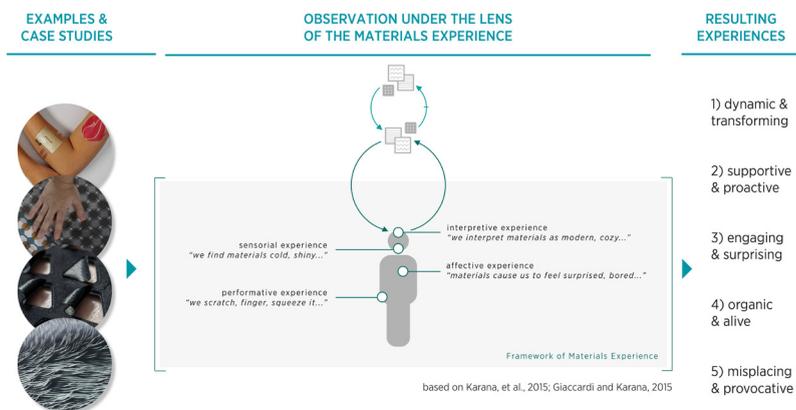


Fig. 1 - The model used for the observation of ICS Materials examples and case studies, using the lens of Materials Experience (Karana et al., 2015; Giaccardi and Karana, 2015). In the picture the following examples are shown: DuoSkin¹ (Kao et al., 2016), Recurring Patterns Project² (Nilsson et al., 2011), BioLogic fabric³ (Yao et al., 2015), Transformative Paper⁴ (Holzbach, 2015)

General considerations about experiencing ICS Materials

Among the results, prominent findings unfold the relationship between temporal and static expressions. From the observation of samples of best examples and case studies, the first reflection regards the three levels of the Materials Experience defined as Sensorial, Affective and Interpretive. At first, what emerges is a substantial similarity between ICS materials and traditional ones, when the material is latent, i.e., performing no behaviour. Therefore, they are perceived as traditional ones (e.g., paper, leather, concrete, fabrics, etc.), because at a sensorial level the impression is indeed given by the mate-

¹DuoSkin by MIT Media Lab and Microsoft Research, 2016 (Kao, et al., 2016). Courtesy of Cindy Hsin-Liu Kao.

² Recurring Patterns Project by Smart Textiles Design Lab at the Swedish School of Textiles, 2011 (Nilsson et al., 2011). Courtesy of Linda Worbin and the Smart Textiles Design Lab at the Swedish School of Textiles.

³ BioLogic by MIT Media Lab, Lining Yao, 2015 (Yao, et al., 2015). Courtesy of Lining Yao.

⁴ Transformative Paper by Florian Hundt, a result of the cooperation "Intuitive brain" between Prof. Dr.-Ing. Markus Holzbach, Institute for Materialdesign IMD, HfG Offenbach and BMW AG, 2015 (Holzbach, 2015; Parisi, Holzbach and Rognoli, 2021). Courtesy of Markus Holzbach.

rial used as a support. This is due to the seamless integration of technology. The same implications regard the affective and interpretative levels that depend on the previous experience the user had with the material used as a support. While, in static conditions, the materials do not differ from traditional ones, instead they trigger different perceptions, emotions and interpretations while performing their programmed behaviour. Therefore, behaviours and dynamic expressions influence the experience modifying all the layers of experience.

Dynamic and transforming experience

In all the case studies observed, it is evident that, compared with traditional materials, the qualities of ICS materials are dynamic, reversible, and adapting in response to external stimuli. In other words, ICS materials are not latent; instead, they are constantly changing, modifying their qualities over time. A dynamic materials experience has both a transforming and transformative nature. The transforming nature is described and articulated by the concept of *becoming materials* (Bergström et al., 2010), focusing on smart materials as fundamentally temporal entities that can have multiple states of expression over time that can be controlled by designers to shape some experiences intentionally. The transformational quality of these materials produces new affordances, stimulates new communication languages, and triggers new way of interacting with the user, playing a big role in shaping people's social behaviours and practices, due to their ability to establish emotional and affective interactions (Minuto, Pittarello and Nijholt, 2014; Rognoli, 2015).

Supportive and proactive experience

To their best degree of smartness, interaction, and connectivity, such materials enable proactive experiences. Not only they sense and respond to input, but they can establish a relationship or a dialogue with the user or the environment, or even between the user and the environment. They respond to input from users or environment activity, making invisible data evident and, in a way, tangible to the users by means of movements, vibrations, sounds, colour-changes, or light-emission. Therefore, the users are encouraged to respond to the materials' feedback, changing their ways of doing or their habits for better. This can regard data about air or noise pollution. They can

make information more accessible to the user, informing and enabling them to respond to it and act more aware - and proactively - in their daily life. Moreover, ICS materials can make objects, wearables, and spaces constantly monitoring biometrics and adapting to the users' needs for their wellbeing, with significant implications in health prevention and rehabilitation. Interacting with dynamic materials can lead to personalized relationships with the material. Personal and unique aspects of this relationship between the user and the material are derived from the interpretative component of the materials experience. This is especially the case in ICS Materials that change to suit different conditions.

Engaging and surprising experience

ICS materials enhance the aesthetic enjoyment by triggering the effect of surprise and by creating entertaining multi-sensory experiences. Much like for natural and biological organisms, dynamism and reactivity of ICS Materials offer an element of surprise and unpredictability which drives people curiosity. However, digital technology allows us to control such unpredictability. ICS Materials can 'integrate the unexpected' because they highlight the visual-touching incongruence as an underlying connection with the sense of surprise in materials (Ludden, Schifferstein and Hekkert, 2008; 2012). Often the incongruence is even improved by the contrast between the familiar look and feel of the material in its static form, and the surprising and dynamic expression in its temporal form. In many cases, users more likely interact with the material when static, while when reacting at first preferred to observe instead of touching. However, after some time, surprise and positive feedback may leave room to neutral feedback. This issue can be addressed by creating complex dynamic interaction, by layers of temporal forms of different typology that may contribute to establishing a deeper emotional connection with the user. An example is combining programmed behaviour of actuators, with reversible behaviours of smart materials, with irreversible behaviours of the supporting material. The suggested combination will create diverse and ever-changing alterations, relations and behaviours in the material and its components keeping users' surprise and curiosity stimulated over time.

Organic and alive experience

Often, users express analogies between ICS materials and nature, because of their dynamic behaviours which emulate or resemble the ones of living organisms. Slow behaviours are considered more organic and nature-inspired and are perceived as more positive, evocative and emotional. Some case studies, in their latent dimension, suggested how the material would react, in an organic manner and by exposing a principle of accordance between shape, material, and behaviours. This evokes positive connections. In many cases, the inspiration to natural behaviours of animals or vegetal organisms is evident, and biomimicry arises as an approach to transfer the that natural feeling and to create more intuitive interaction.

Misplacing and provocative experience

While some people had a positive reception to the materials, mainly related to the feeling of surprise and wonder, for others the behaviours itself was considered as obtrusive or even aggressive. Although behaviours typical of nature and inspired by it are generally perceived as positive, evoking and relaxing the users, the ‘living’ behaviour provided by the digital components of these materials can cause emotional discomfort on the other hand. A material with an agency can be perceived as obtrusive, i.e., physically and sensory evident in an unwelcome and intrusive way, causing physical and emotional distress. To this extent, they have to be considered as uncertain and provocative. Out of their comfort zone, the users are challenged to find personal and unique ways to interact with the materials and objects. The observed cases reveal a tension between the sensorial and emotional comfort and enjoyment, and the possible feeling of discomfort and anxiety provoked by the behaviours.

5. Conclusions and remarks on ICS Materials and experience

In this chapter, we presented ICS Materials as a phenomenon enabling novel and meaningful materials experience, thanks to the leverage of material expressive-sensorial qualities and interactive behaviours. By observing ICS Materials examples through workshops, observations, questionnaires and qualitative studies through the lens of Materials experience, we present-

ed some relevant findings of the main experiences they enable and imply. We clustered them into some emerging experiential patterns: 1) dynamic and transforming; 2) supportive and proactive; 3) engaging and surprising; 4) organic and alive; 5) misplacing and provocative experiences.

In these experiences, digital and material are not distinctive, but entangled elements of the same cognitive and design process. Digital, materials and design are no longer separated things but are porous elements of the same process of research, design and invention (Pink et al., 2016). The work of blending the technology and materials, which are elements with different properties, qualities and also affordances, for creating new emerging materials experiences, becomes the task of the designer. Indeed, ICS Materials are emerging materials with extraordinary characteristics unfolding new practices to shape and control them. They require a new set of approaches, tools, and techniques to be integrated into design practice and education.

Smart materials and interactive technologies entail new tasks and challenges for designers who have to ensure that - in achieving what is technically feasible - the well-being and sense-aesthetic engagement of people is preserved (Ritter, 2006). In particular, designers have to be careful about the risk to design something obtrusive - i.e., causing physical, emotional and affective distress - or meaningless for users. They can control it by tuning material qualities and practices, achieving meaningful materials experiences.

It is difficult to describe the qualities of ICS materials as they continue to change and transform themselves. This is also a limitation for the tools and models hypothesized for their understanding and characterization. These must be redesigned to provide the temporal perspective able to read the dynamic and changing experiences that ICS materials, as flexible and programmable elements, can create. Within ICS Materials, designers can also become programmers (Vallgård et al., 2017) of the qualities of materials, designing interactions and responses as part of the expressive-sensory and experiential characterization of the material. In fact, ICS materials are incredibly flexible in providing countless qualities related to materials experience at different levels. The materials are, therefore, no longer chosen only for their properties but are programmed, designed, modified, processed to respond to specific needs or situations.

In this chapter, we have presented the definition of Interactive Connected Smart (ICS) Materials and have tried to identify their main constituent elements. Finally, we introduced the principal experiences enabled and suggested by these materials. Concluding, therefore, beyond the programming skills implicit in ICS materials, and their interactive, connected and intelligent na-

ture, it was understood how these materials offer great opportunities in terms of tangible interaction. They are opening significant developments and new paradigms for product and interaction designers, which could act simultaneously on different levels of the design project. By adjusting the layers of experience to consciousness, designers play a decisive role by contributing to the creation of meaningful material experiences, meeting people's appreciation concerning specific materials and improving values and behaviours in society.

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2. Mapping ICS Materials: framing the complexity of hybrid material systems

by *Stefano Parisi and Venere Ferraro*
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1. The rise of hybrid material systems

The rapid development of emerging technologies, of the phenomenon of the Internet of things (IoT) and generally speaking of smart interactive products have been changing the way we live and interact with each other. As one of the main consequences of the rise of smartness in everyday life, we are witnessing a change in materials as well, moving from traditional materials characterized by being latent, to emerging materials with adaptive and dynamic capabilities responding to the need of users' demands for smartness. This is possible thanks to the increasing miniaturization of technologies (sensors and actuators) and their integration into materials, generating material systems defined by a hybrid nature and interactive behaviours. They are able to sense human parameters and the surrounding, light-up, change shape, process signals, act as an interface so that becoming a new medium between users and the environment. This new class of materials opens up several opportunities for user experience and engagement thanks to novel channels of interaction able to create surprising experiences as well. Moreover, this phenomenon poses new challenges and requirement for the design discipline to be faced.

Scholars in Design and Human-Computer Interaction (HCI) who have been studying the subject elaborated different concepts and definitions, as follows. Brownell (2014) came up with the concept of *expanded matter* – or *X-matter*. This definition identifies materials effectively enhanced with additional capacities such as tracking, sensing, responding, interacting, by the integration of information technologies. They are *metamaterials* that have properties that they would not otherwise have, due to the way they are structured or layered and work systemically. The definition of *Augmented Materials* (Razzaque et al., 2013) refers to materials with generic physical and computational properties, in which electronics are seamless and embed-

ded during the fabrication of the material. As a proof of concept, projects such as *Smart Dust* (Warneke et al., 2001) will deliver incredibly miniaturized microelectromechanical systems that will bring sensing and communication capabilities at the level of the material itself as opposed to the level of the entire object as it is today.

Computational Composites (Vallgård and Sokoler, 2010; Vallgård and Redström, 2007; Vallgård, 2009) identifies composite materials in which at least one of the components has computational capabilities. The definition *Smart Material Composites* (Barati, Karana and Hekkert, 2019; Barati, Giaccardi and Karana, 2018; Barati, 2019) refers to the combination of smart materials working together and creating complex interactions, for example, light-emitting electroluminescent smart material in combination with electricity-generating piezoelectric smart material. In literature, we also find the definition of *Smart Composite Material Systems* (Kelly, Davidson and Uchino, 2017), as a combination of smart materials delivering sensor systems, actuating mechanisms, and control systems. Finally, the idea of a systemic composition of materials to provide enhanced dynamic sensing, communicating, and interacting capabilities is vital in *Interactive Connected Smart Materials* (ICS Materials).

Those new materials born in the intersection of material science and interaction design disciplines can be defined as **Hybrid Material Systems**: material-based systems encompassing different components such as inactive materials, smart material components, sensors, actuators, computational layers, etc. In literature, we find the definition of *Hybrid Materials*, as a compound of both organic and inorganic components, including micro components of a different nature, such as electronics (Saveleva et al., 2019). According to Ritter (2006), *hybrid materials* are manufactured by combining at least two different components, e.g., biological with synthetic components. Ritter affirms the potential of Smart Materials to be combined in a system to create complex interactions.

In this chapter, we put the attention on a specific phenomenon within hybrid materials systems that is the rise of ICS Materials, an acronym that stands for Interactive, Connected, and Smart Materials. So far, examples of these materials can be found available both in limited commercial materials – still with many application limitations, for example, e-textiles – and in the form of experimental or underdeveloped materials and surfaces, composites, and functional components, and systems (Coelho et al., 2009; Vallgård and Sokoler, 2010; Razzaque, Dobson and Delaney, 2013; Yao et al., 2015; Kao et al., 2015).

Here, we will present a map framing the different dimensions and nature of ICS Materials as result of a hand-on workshop carried out by scholars at

the Department of Design of Politecnico di Milano (Parisi et al., 2018). The method we used will be presented, the workshop will be described, the ICS Materials map will be framed, and their constraints, potentials and impact on design will be discussed.

2. Method: participatory workshop

The ICS Materials map was framed and established during a hands-on workshop carried out as an activity within the research project ‘ICS Materials’ funded by FARB (Fondo di Ateneo per la Ricerca di Base), Politecnico di Milano, and carried out by a multidisciplinary team of researchers of the Department of Design. The project covered different activities from a literature review to a series of seminars and workshop with both students and scholars. The primary research phase aimed at an understanding of the area of investigation (materials and interactions) and at collecting diversified case studies covering materials, products, components, systems, installations and demonstrators, showing any characteristics of interactivity, connectivity, and smartness. Criteria for the selection of examples were set as follows: material-based item showing a smart, interactive, or connecting behaviours, regardless of the nature of their inputs, means, and outputs, to cover a full spectrum of examples.

The peculiar and unclassified nature of ninety-eight case studies collected, pose the need for mapping and classifying them thorough a participatory session. We realized that we were facing a so-called *ill-defined/wicked problem*. It has been proved that participatory tools and methods are used to stimulate creativity, and problem-definition and -solving capabilities, as a scaffold for collective creativity (Sanders and Stappers, 2012). Collective creativity is crucial to solving wicked problems (Buchanan, 1992), i.e. the ones that are “difficult or impossible to solve because of incomplete, contradictory, complex interdependencies” (Rittel and Webber, 1973).

In a typical format of a participatory workshop, everyone participates to discussions and reflects by contributing to the topic with their own experiences. The workshop arises as a method for qualitative research (Ørngreen and Levinsen, 2017) and provide an opportunity for researchers to identify and explore relevant topics in a domain, which are not evident to researchers or participants before the workshop. Such a method is particularly helpful in understanding the so-called wicked problems and open up new scenario, e.g., for research trajectories and map.

Based on this grounding, we set a participatory and hands-on workshop of a limited duration targeted to the group of participants involved into the project. Following the strategies and guidelines suggested by the literature (Chambers, 2002; MacDonald and Headlam, 2016), a workshop of four hours was organized and carried out. The workshop was structured into three main consequential activities. The aim of the workshop was threefold: fulfilling the purpose of the research; alignment and knowledge sharing between the researchers; allowing researchers to achieve findings or inspirations related to their specific research interests.

From a practical point of view, in participatory workshops there is a strong focus on collaboration, sharing ideas and coming up with joint solutions. We then set a dynamic group with researchers having expertise from interaction to product design to material science, breaking down roles. During the workshop, we encouraged engagement through collaborative discussions and feedback between the ones who had the role of facilitators and the participants (Ahmed and Asraf, 2018).

3. 'Mapping ICS Materials' hands-on workshop

The workshop lasted four hours and was framed into three steps. It involved nine scholars of the Design Department of the Politecnico di Milano participating to the project ICS Materials. Three of them covered the role of facilitators of the activity. After a presentation of the aim, structure and recommendation about the workshop by the facilitators (fifteen minutes), three activities were consequently carried out, as follows.

In the first step (one hour) ninety-eight cards representing the collected case studies were presented to the nine participants who were divided into three groups (Fig. 1). Each card presents one example with the support of visual and textual information: name of the project, name of the author, a short text describing how it works and how it behaves. A different deck of cards (approximately thirty-three cards in each deck), was provided. With the support of the cards, each group explored the best examples and tried to categorize the case studies according to different criteria, e.g. the Material Experience (Karana, Pedgley and Rognoli, 2015; Giaccardi and Karana, 2015) they enable, typology of items, technological complexity, the kind of interaction considering inputs, means, outputs, and others, and others. In this activity, white posters and sticky notes were used as support for the small group discussion: participants could write their thoughts, ideas, key issues and keywords on them or the cards themselves. Cards and sticky notes could be clustered on the poster to identify categories.

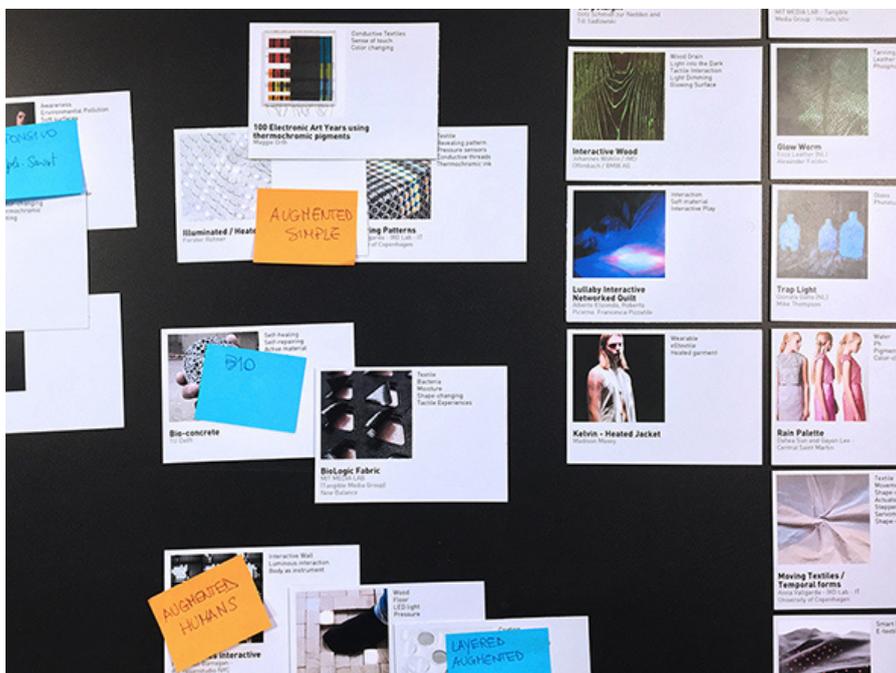


Fig. 1 - Overview of a selection of cards used during the workshop

Afterwards, in a second step (forty-five minutes), each group **presented its attempt to categorize ICS materials**, by showing their posters and articulating the results of the small group discussion (Fig. 2).



Fig. 2 - Data produced by participant's group to show the grouping of the cards

Finally, in the third step (one hour and thirty minutes) **an open discussion** among the three groups was performed. The discussion was focused on which lens to choose in order to map the ICS Materials such as (i) typology of case studies (enabling technologies or components, research and experimental demonstrators, systems or products including enabling technologies, platforms, materials and composite materials); (ii) Technology-driven material (the designer uses the material or technology because of their performances) Vs. Design-driven material (the designer “designs” the material according to a purpose to reach); (iii) the technological complexity by deconstructing materials into their components; (iv) the kind of interaction proposed by the materials (active, reactive, analogical, digital, biological, etc.); (v) the application sectors; (vi) the manufacturing processes and techniques.

Since the ICS materials concept is based on the notion of interactive, connected, and smart materials, at the end of discussion all the participants agreed on using the degree of “interaction, connection, and smartness” as a lens to map them. Therefore, we conceptually modelled a tentative scale on which was possible to place the examples, from the less to the most interactive, connected, and smart ones. Early, we argued and validated that this criterion is strongly related to the technological and systemic complexity of such materials. In the following section, the synthesis of the resulting map is presented.

During the last two phases, a whiteboard was used by one facilitator to write down and visualize key information and processes emerged from the small group discussion presentation and collective open discussion. Another facilitator was in charge of moderating and encouraging the discussion. At the end of the workshop, facilitators presented a resume of the preliminary findings that emerged from the discussion and informed about the following activities, that are analysis of collected data and results formalization and visualization.

Data collection was done by keeping all the posters, notes, and cards as a record, a tool for data collection and analysis (Fig 3). At the end of the workshop, they were filled with notes, sketches, schemes containing data generated by the smaller groups’ discussions. Also, audio-recording was used to collect data and opinions during the collective discussion and presentation for the results. The whiteboard used to record and organise the main relevant points of the debate was photographed and used for data collection. Also, the facilitator took notes during the activity. Collected data from all these sources were analysed. The obtained information was organised in a graphical representation of the ICS Materials map that is presented in the following section.

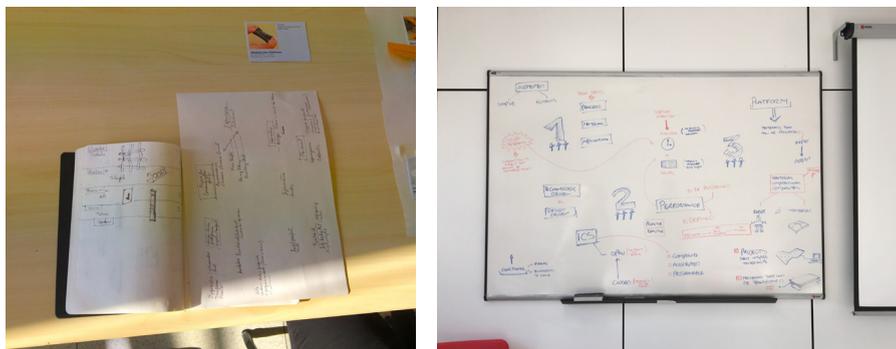


Fig. 3 - Data collected during the workshop with the support of provided tools shown here as evidences of the activity

4. The ICS Materials Map

As a result of the workshop, we propose a tentative map (Fig. 4), as a tool for understanding and framing ICS Materials (Parisi et al., 2018). It is an inclusive model encompassing different classes of materials, according to their degree of interactivity, smartness, and connectivity, and their related technological and systemic complexity. The funnel-like graphical representation is intended to be read from top to bottom. The resulting categories are *inactive materials*, *reactive materials*, and *proactive materials*.

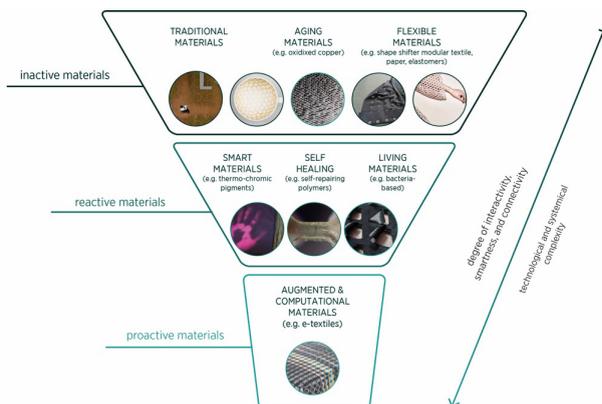


Fig. 4 - The tentative map of ICS Materials as resulted from the workshop 'Mapping ICS Materials'

Inactive Materials category includes traditional material with no explicit or direct interaction or allowing interaction at a very low degree. They are latent, that means that they do not show the ability to react and connect quickly. In other words, they are mostly behaving in a passive manner. Thanks to their chemical or structural characteristics, they are subjected to establish some sorts of interaction with the users and the environment along the time. Among them, some materials show this in a more evident or expressive way, like ageing materials, as oxidizing copper, or flexible materials, like paper or elastomers. Their behaviours cannot be designed or programmed, but only exploited by people, and can be the supporting materials for the following classes.

Reactive Materials include smart materials or combinations of inactive materials with smart materials components, e.g. thermochromic inks (Addington and Schodek, 2014; Ritter, 2006). They display changeable properties and can reversibly change some features such as colour or shape, in response to an external stimulus. Examples are thermo-chromic and photochromic polymers, shape memory alloys and piezoelectric materials. Instead, a limited number of examples use living and growing organisms as biosensor and bio-activators to sense and react to stimuli, as bacteria. Because they are living organisms, they have a certain degree of intelligence and unpredictability. We might include into this category also self-healing or self-repairing materials, substances with the ability to automatically repair any damage to themselves without an external diagnosis of the damage or human intervention (Bekas et al., 2016), by inner properties of the material or with the support or embedded components or organisms. Reactive materials have a higher degree of interactivity compared with the Inactive materials, but their connectivity is low. They can be seen as closed materials because their performances are designed in the fabrication stage. However, if these materials are combined with other entities in a more complex and intelligent system, they can improve their connectivity and smartness. This means that they can be applied “as a critical part of smart systems” (Ferrara and Bengisu, 2013).

Proactive Materials category is the one that best fits the definition of ICS Materials, having major interactive, connecting, and smart capability to their greatest extent. They represent complex and intelligent systems of material components based on the combinations of inactive materials or reactive materials with embedded digital, electronic and computational technology in the form of sensors and actuators and connected with external or embedded computers or processors and source of energy. In other words, proactive materials are the interdependent combination of *passive* sensing and interconnecting systems (for example, sensors and conductive sensitive

materials, as yarns, coatings, and inks for printed circuits) and *active* actuating mechanisms (actuators or responsive materials), by means of a control system. Therefore, they are able not only to sense and to act. Also, they respond to the user behaviour, communicate information basing on that behaviour, and make the user behave in response to it, encouraging informed and pro-active interaction. Proactive materials show a very high degree of interactivity, connective abilities, and smartness. When compared to reactive material, they are more advanced as they can be potentially programmed and re-programmed at every stage of fabrication and use (Vallgård et al., 2016). This acknowledges them as transformable (Bergström, 2010) and open materials, unfolding new scenarios of interaction and a new concept of smartness, as they allow designers, engineers, makers, creatives, and users to work on open materials, to obtain results, qualities and expressions.

5. Discussion and final remarks

In this chapter, we discussed and presented the rise of a new class of materials called ICS (Interactive Connective Smart) Materials as part of the emerging phenomenon of Hybrid Material Systems.

One crucial aspect emerging from the analysis is that ICS Materials are made of components – *layers* or *building blocks* – that have physical and interactive natures. Even though in some cases it is difficult to define a neat separation between what is material and what is technology, we can simplify by stating that some of these components belong conventionally to the domain of materials, others to technologies. Using the same simplification, we can say that some of the elements of the systems have tangible qualities – mainly latent –, other have interactive – and dynamic – qualities. Due to this complexity, ICS Materials as Hybrid Material Systems are situated in the intersection of material science, interaction design, and product design. This position has implications into knowledge and skills that are needed to design with and for these materials. For instance, regarding the skills needed to make the system functional, programming skills are needed to make the technology functioning, making skills to craft the material, and design skills to integrate them into a system. Similar considerations can be made about the knowledge and competences required to make the system meaningful.

ICS Materials need to be designed and manufactured on purpose; this aspect creates a new opportunity for designers to code and shape the materials according to the customized needs of specific use or context responding to functional, aesthetic and experiential requirements.

The complex nature of ICS Materials as hybrid systems is reflected by concepts and theories emerging in HCI and Interaction design field. On the one hand, the relevance of the tangible and sensorial engagement of the user with interactive objects is promoted by the notion of *material turn* (Robles and Wiberg, 2010), *material move* (Fernaes and Sundström, 2012) and *material lens* (Wiberg, 2014). On the other hand, instead, a behaviourist view of interaction design (Saffer, 2009) describes the act of design as “defining the behaviour of artefacts, environments, and systems” (Forlizzi and Reimann, 1999, via Saffer, 2009), prioritizing behavioural aspects over tangible ones.

The map produced as a result of the workshop and presented in this chapter is a tentative and open-ended model aiming at starting positioning and discussing ICS Materials definition with the support of best examples and a taxonomy. The systematic classification of materials is an ongoing effort, thus continuously subjected to re-categorization and extensions, considering other criteria and by furthering the collection of case studies.

The lens used for the categorization of the examples is one of the degrees of interactivity, connectivity, and smartness relying on the definition of ICS Materials. Three main categories are emerging: inactive, reactive, and proactive materials. Only the last category complies the definition of ICS Materials entirely: materials systems able to establish a two-way exchange of information, to respond contextually and reversibly to external stimuli, linked to another entity or an external source, and programmable not only through software (see chapter 2.1). The categories present similarities and find validation in others’ works. This is the case for the existing categories of *passive smart*, *active smart*, and *very smart* textiles (Wu and Li, 2019) or *passive*, *active* and *intelligent systems* (Kelly, Davidson and Uchino, 2017), among others.

Other criteria for the mapping and taxonomy can be investigated in future activities, to find alternative and complementing systematization and position of ICS Materials, for example, application sectors, enabled experiences, and manufacturing process and techniques. In other chapters of this book, several of these aspects and opportunities will be unfolded and presented by case studies.

Considering the complex nature of being both behaviour- and material-based systems, ICS Materials unfolds several user experiences – for instance, surprising, engaging, supportive, assistive – and application in different fields such as wearables for sports, health, and entertainment (see chapter 3.4), exhibition and architecture (see chapter 3.2) IoT and smart products (see chapter 3.3), nautical (see chapter 3.5), and surfaces (see chapter 3.1). Since ICS Materials introduce to products and systems new properties such

as interactivity and temporality, they can envision a new *dialogue* - between the user and the products/systems - that is experienced on both physical (shape and technology) and emotional (positive/negative) level.

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Part Three
Defininition of advanced methods and scenarios
for the application of ICS Materials

1. The Ultra Surfaces Vision

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The mutual contact between humans and objects or environments happens through surfaces. Testing surfaces with senses, human beings experience the world, understand its characteristics, and the relationships between the different parties. Through the interaction with surfaces, we appreciate or despise the world around us. Experiencing surfaces arouses a variety of emotions.

Since ancient times the role of surfaces in the perception-based process has been investigated. The Epicurean philosopher Lucretius (c. 99 - 55 BC) described the surface as the manifestation of the substance of things and as the place of the imagination. For artists, architects, and designers, the surface has been the main mean of expression, support for imagination, and visual and tactile modeling for aesthetic enjoyment.

The surface in itself is a complex entity that includes textures, patterns, and a variety of other *soft qualities* (colour, smell, temperature, weight, etc.) that convey a message about the design intention. Given a specific context and a beholder, the sensory interaction with the surface activates an intimate touch and an interpretation process that generate the meaning to space or a product.

If in contemporary times, the surface-screen has achieved the role of the leading media of communication, sharing, and expressing emotions (Bruno, 2014), in the digital era, the phygital (physical + digital) is opening a new potential to reshape human experience. In everyday life, the interactions between peoples and objects through the IoT can happen in two parallel channels, the physical and the digital one. In this last channel, we interact through small surfaces like screens, touchpads, keyboards, and device interfaces systems. The limited dimension and poor sensory qualities of these interaction surfaces, is often alienating because they distance us from the multisensory

richness of the tangible physical world. For this reason, the design community has drawn attention to a new hybrid materiality to rediscover the pleasure of the world, increasing our experience with the digital potentialities. From Design to Humanities, from Human-Computer Interaction to Electronic Engineering, the scientific communities are now focusing on this new materiality that includes digital and analogical dimensions, and its relationship to aesthetics, technology, and temporality.

Investigating the possible relationship between the physical and digital dimension of new surfaces has been the main task of the activities we conducted within the ICS Materials research. After approaching subtle link connecting surfaces, design, and emotional experience, we move on according to design praxis, applied during the workshop *Ultra Surfaces*. The materials of reference in our analysis are the industrial laminated surfaces cellulose-based, currently produced by two of Italian companies that were invited to collaborate in the educational activities/ /research, to be inspired by new visions and future scenarios.

1. The Material Surface Industry Technical Research

Nowadays, a market approach based exclusively on costs and technical properties is outdated. New industrial approaches take customer or consumer request as the primary key to enables more effective models of product-service system innovation. The attention to physical appearance and user satisfaction assumes increasing importance because it is strictly related to human expectations, connecting the aesthetic dimension to functional reasoning.

Meanwhile, in several material industries (from glass to laminated composites), the electronics integration into physical components by embedding a growing number of economically ready-to-use technologies, is acquiring a strategic role to compete in the market. This is a big opportunity to increase product usability, aesthetics and customization. The integration of smart layers, sensors technologies, and patented AI is a suitable and versatile approach to augment product performance starting from the material surfaces and generate updated, proactive, and tangible user interfaces. Such innovation is capturing a growing consumer interest, especially considering applications in fashion, product and interior design where smart behaviors, interactivity, and connectivity are intriguing concepts to raise the value of the products.

Among the most promising technologies, thin-films offer a host of advantages such as high compatibility with various materials, high scalability,

and addition to seamless heterogeneous integration. There is considerable scope for flexible electronics of thin films applications in the health sector, in environmental monitoring, human-machine interactivity, energy conversion, sensor support communication, and wireless networks (Nathan et al., 2012). With the achievement of large dimensions production, thin-films offer opportunities for product innovation. Thanks to films applications, product surfaces are reaching multi-touch capacities making closer and based in sensory perception the relationship with users. Thanks to thermochromic and photochromic layers, the transparency of glasses can vary. In architecture applications smart glass can separate or connect inside and outside, proposing a variable and controllable on time vision, making possible the evolution of usual perceptive experiences (Ferrara and Bengisu, 2014).

Another promising industry for the integration of electronics into materials is the paper one is the paper manufacturing. In the last decade, the scientific research proposed printed electronics to enrich paper-based surfaces with barcodes, QRcodes, RFID tags, and conductive traces, and also electroluminescent foils or segments, showing the possibilities to increase the connectivity and the perceived value of such an underestimated material (Klamka and Dachselt, 2017). Today this industry is particularly interested in imbuing elements with sensing capabilities applying instrumental materials, like conductive paints, silver drew lines, copper stickers/tape, printed inks. These enable capacitive touch-sensing elements, such as buttons and sliders, without wires or visible electronics and connectors. New surfaces for interior can integrate interactive wallpapers, made of conductive paint, and thin electronics, without losing the sensory richness and flexibility of paper, supporting several applications, including interactive educational tools. Experimental examples of wallpapers serve as ambient information displays, giving feedbacks with light-emitting surfaces (Huang and Waldvogel, 2005), or communicating with other networked devices.

Start-ups are standing out along the strategy of seamlessly merging the physical matter and data without the need for keyboards, buttons, or touchscreens. Among the most interesting example, Hypersurface (2018) applies advanced sensor tech and AI to convert any surface into a smart one able to recognize gestures and other events. This patented technology - based on fog computing and composed of a chip connected to a network of vibration sensors controlled by algorithms - increases the surface performance. The system detects vibration patterns from human gestures interaction (like knocking, pinching, taps, swipes, etc.) or object collisions on the surface. Instantly, the “Mogees” embedded AI interprets the data vibration, converting them into a digital command that activates a specific feedback, like a designed sound or a speaking voice. As regards the integration possibility, Hypersurface uses

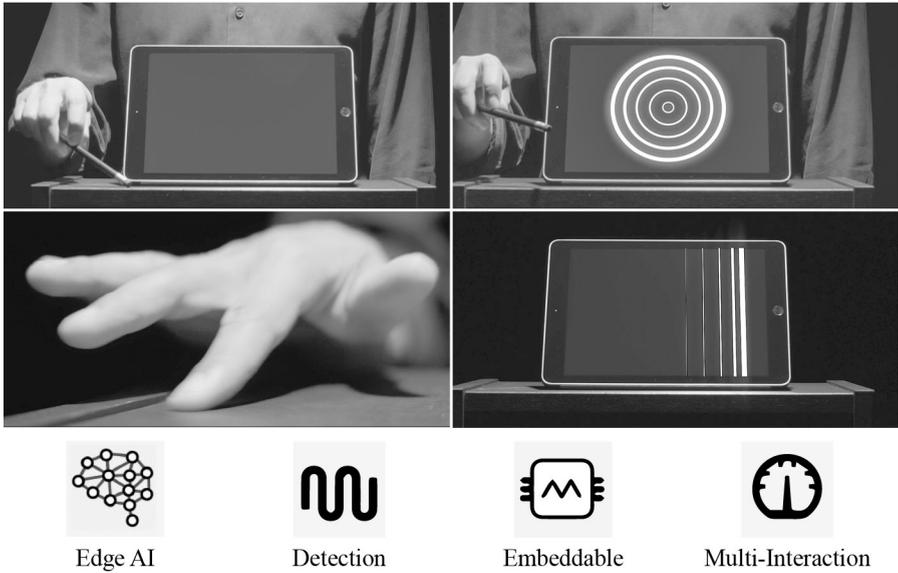


Fig. 1 - Hypersurface video frames. Courtesy Hypersurface

standard vibration sensors, and the software is a platform-agnostic so that it can run on standard chipsets. This technology offers a new *open platform* to add to any surface functions and features, transforming it into an almost-living-entity, with which interact through a gestural language, customized for each application. At the same time, it augments users' experience by adding a living touch, an interactive behaviour.

We are already experiencing a massive interest in new creative entrepreneurship opened to fabrication reshaping processes for a next products generation. Today, the design discourse about *ICS Materiality* (Rognoli et al., 2016; Ferrara et al., 2018; Parisi et al., 2018) allows to go beyond the previous experiences of innovative materials, to dive into the benefits that technological advances can bring to the user's experience, fully experimenting the multisensoriality that the *phygital* allows.

2. The Ultra Surfaces Vision

Ultra Surfaces (USs) is a unique design vision we have been adopted within the framework of *ICS Materials* to generate Next Design Scenarios of material surfaces. The vision was achieved thanks to the research carried out in recent years within the Material Design Culture Research Centre (MADEC)¹, which is deeply investigating the relationship between material for design and pragmatic aesthetics².

The USs vision enables a seamless fusion of physical matter and digital performance. Digital computationally augmented surfaces acquire intelligence and extraordinary interactive qualities. These are likely to enrich the users' perception with a multisensory involvement. The USs can contribute to augment the interaction between man-object and environment-people in a meaningful way.

In the USs vision, the possibilities to overcome the limits of human perception, with the aim of improving daily interaction in term of psycho-physical well-being are limited only by creative imagination. Connecting Design-Driven Material Innovation Methodology (D-DMI), Research-through-design, and User Experience - based analysis allow us outlining USs next future scenarios and concepts in which the human interaction with surfaces turns into a pervasive everyday *Smart Aesthetics Experience* (SAE). This last is a new kind of experience, mainly originated by interactive technologies, impacting at the emotional level, encoding new attitudes, feedbacks, gestures, and communicational issues (Ferrara and Russo, 2018). SAE relies on both mind and body stimuli, as well as being rooted in the socio-cultural context of people's everyday life. It promotes curiosity, engagement, and imagination in the exploration of an interactive system.

Designing the USs requires the designer's empathy to users multisensory involvement during the interaction. It need to understand the user pleasure coming from the sensory perception as well as the interpretative process, and consequently evaluate emotional responses, aesthetic judgments, and on product value. If well designed, an USs could *materialize* pleasurable Smart User Experiences through full-body involvements.

¹ MADEC is also an international network that was founded in 2013 in the Design Department of Politecnico di Milano, thanks to the homonymous research FARB 2013. For more information: www.madec.polimi.it.

² Regarding this specific topic, the research conducted in 2018 by Anna Cecilia Russo (fellow researcher) was fundamental. This study has been carried out in partnership with ABET Laminati, a leader company in the production of plastic laminated surfaces, characterized by a wide variety of textures.

3. Workshop Scope and Approach

According to the approach of Politecnico di Milano Design School that integrates scientific research with didactic, in the academic year 2018-2019, we involved forty-five designers-to-be during their Product Design Graduation Lab, in a design workshop. The goal was to envision Next Future Scenarios of the US. During a month, students experienced a cross-disciplinary design process in cooperation with two manufacturing companies of laminated materials (paper and cellulose-based), jointly with a microelectronic company. These were called to collaborate in didactic activities following an open innovation approach.

Planning the workshop required a preliminary phase for the agreement with and among the partner companies, and the team of teachers and tutors. In this phase, we applied a Design-Driven Innovation approach, referring to the D-DMI model, as a way of promoting open innovation processes in the materials field (Ferrara and Lecce, 2017). In a cross-disciplinary and collaborative perspective, D-DIM can activate an osmotic exchange. It helps the design process to fluently put in action critical and speculative thinking about the choice of technologies, questioning the meaning of innovation, and proposing a new vision on the user experience. We shared the vision of Ultra Surfaces and define the design exploration boundaries.

Moreover, according to market trends, we decided to contextualize the design process in two different type of living spaces, domestic, and “alternative care locations” (in outpatient, hospital contexts or located in gyms and schools), focalizing the analysis on everyday human activities. Choosing this generic context, not specific at all, means avoiding any reference to existing products and spaces genres or narrow functional applications. Our aim was triggering a design process where the US performance benefits were the real generators of lifestyle innovation towards a desirable future. We focused on the emerging megatrend “Health and Well Being”, investigating with the lens of user experience, to introduce into user’s daily life sensitizing, be aware, healthy, social/individual activities. The hybridization of *passive* and *proactive* materials, i.e. dynamic/ reversible/ connected/ is a powerful opportunity to design solutions capable of: engaging user in self healthcare; rising comfort and psycho-physical well-being; enhancing a meaningful experience in everyday life

We started the design phase sharing the workshop brief with the students and an overview of smart technology applications in different sectors, from automobiles to urban spaces, and from office to hospitals. Another step was the instructions dispensed by the CEO of the partner company operating in

the field of microelectronics. He introduced students to intelligent systems, provided them with basic knowledge on the possibility of the application of smart technology-ready to use and how implement a smart system on conventional surfaces. It was a starting point to inspire an initial brainstorming about innovative and feasible implementations in terms of smart solutions or even augmented interfaces.

During the workshop, we promoted the discussion about USs vision, the desired SAE, and the *Natural Interaction*, to delineate potentialities and limits in accepting and appreciating the hybridization of the physical dimension with the digital one. Afterwards, we carried out a special session of multisensorial perception exploration with selected materials from the industrial partners.

Multisensorial Perception Exploration

As already discussed in previous studies, multisensory stimulation and involvement now have a big part in the whole Design Thinking approach (Ferrara and Russo, 2019). Providing students with inspirational settings by products and materials multisensory stimulation trains their awareness and aesthetic sensibility, and challenges them in interpreting their full perception. Then, we have gradually moved to a method emphasizing on the individual designers' subjective multisensorial aesthetic experience, starting from haptic interaction to increase their sensibility and skills to design for the whole perceptive experience.

During the workshop exploration phase, we proposed our students a session of tactile investigation and multisensory analysis. We chose four samples of laminated materials produced by the partner companies according to their tactile characteristics (roughness, type of texture, direction, rhythm, etc.), and then about visual aspects (colors, decorative pattern, and other bi-dimensional effects). This tactile and visual exploration was elaborated by the tutor Anna Cecilia Russo and undertaken by students first blindfolded, and only later with open eyes. We pushed young designers to explore surfaces (touching, observing, feeling), and let them express referring to their own experiences (Schon, 1984) to allow their design thinking thriving off surface affordances. We have focus the attention on the experience as a result of a multisensorial/cognitive/affective process and its dual nature as a pleasurable as well as a meaningful dimension (Warell, 2008).

Despite the tacit nature of bodily experiences, for these young designers wasn't that hard to articulate verbally about their sensations, from testing,

as well as letting past experiences memories create meaning about surfaces. During the test, we have also highlighted the use of metaphors to express emotions. These play an important role in existing archetypes and forms of fundamental importance for designing smart products. The materiality awareness activates a construction that involves affordances and symbolic meanings. This construction happens interacting with inactive surfaces, and even more with the proactive ones. Moreover, we considered meaningful teaching the participants to share their perception experiences, to create a common ground of experiences of which inter-subjectively construct meanings (as Josef Albers practiced in his basic design course at the Bauhaus).

Experience-driven Scenarios Envisioning

The multisensorial testing facilitated the accomplishment of crucial design decisions, and during the scenario definition phase was accompanied by a student desk-research on functional opportunities offered by smart technologies and computational systems (search for ready-to-use implementable technologies), ending with the envisioning phase.

In line with a tested approach we already gradually perfected in different workshops (Russo and Ferrara, 2017; Ferrara and Russo, 2018; Ferrara and Russo, 2019), the students were asked to answer the question “What can an Ultra Surface do to increase our experiences?” embracing an interpretative perspective from the initial phase of envisioning scenario. According to design culture, it is not the user the one that must adapt to technology but is the technology that we should shape to create positive experiences for the human being. In such a perspective, we fostered a multidisciplinary attitude, creating an osmotic exchange between design and pragmatic aesthetics, helping the students to structure more critical and speculative thinking.

The envisioning phase was pursued through the definition of the application field, research of inspirational images, and a choice of keywords describing feelings, emotions, and interaction modes along the SAE. The envisioning process had iterations, as suggested by the tutors. Each choice was discussed and detailed according to a Human-Centered Design (HCD) perspective evaluating all the possible implications and the level of emotional involvement generated. Each scenario was presented through conceptual mood boards, collecting reference images from different fields of creativity, envisioning SAE key concepts, and expressive language of the product/surface/space to design.

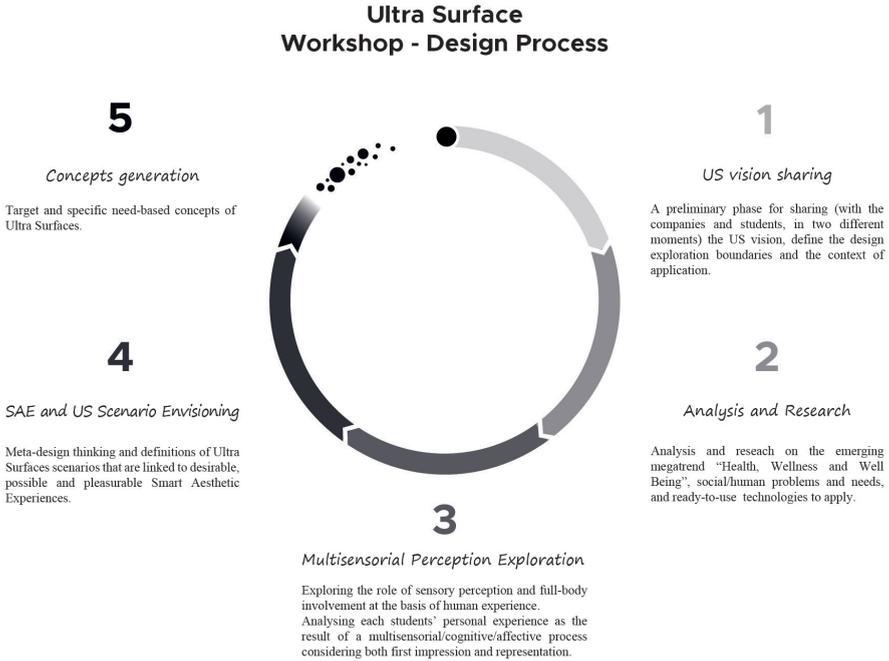


Fig. 2 - Scheme of the design process with different phases

4. USs scenarios and concepts

We will now present a selection of five scenarios of USs within domestic spaces and care contexts, based on users' experience-driven innovation activities.

The first one, "Empathic Haptic Grace", came from an exploration of body language and gestures, especially about how children and teen-agers creatively interact with invisible forces of their thought. A team of students with art-dance experiences chose to envision a full-body movement interaction that triggers personal space and kinetic sensations-based experiences (as input and output). Rather than passive users in meaningless space with a screen bringing all the actions from the elsewhere, the scenario envisions an alternative mode to interact with products, where the body is shaping a harmonic and empathic conversation.

The scenario recalls the *kinaesthetic interaction* framework of Fogtman (2007) for two reasons: to deal with the growing problem of unhealthy lifestyle caused by a lack of motion; and to take advantage of stress releasing movement, which is also influence our wellness. Therefore, using the whole-body during interactions gives the user a physical and emotional experience.

In the following design phase, this scenario generated, among others, the *Euritmia* concept, a system of interactive boards for haptic emphasize areas, designed for a childcare center. The design of this system is inspired by the Eurythmy, the art of movement therapy by Rudolf Steiner (1921), useful for rehabilitation, during convalescence, and the prevention of various physical diseases. The surface is made of a soft-touch paper with integrated light led. While the interactive input is a gesture, the output is a flowing visual sha-



Fig. 3 - Empathic Haptic Grace Scenario

pe and a light movement. It helps children to reproduce movements or sequences related to their healing sessions. An embedded system of proximity sensors activates LEDs that turn gradually to light shaping elegant lines to enhance users' kinetic involvement.

The second scenario is “Conscious Diet Surface”, a surface able to support users in the everyday diet experience. It helps to increase the competence on a diet, and the awareness of user food choices. In this scenario, the kitchen surfaces at home or tables at the restaurant can deal with users' needs in terms of daily intake of water and nutrients and suggests the right meal. It can give feedbacks trough information and advice to push the user to start a healthy diet, providing data about the right portions, cooking methods, and the nutrients intake. The concepts by students also include *I-Tabula*, a table with a smooth wood surface able to recognize users, and suggests meals de-

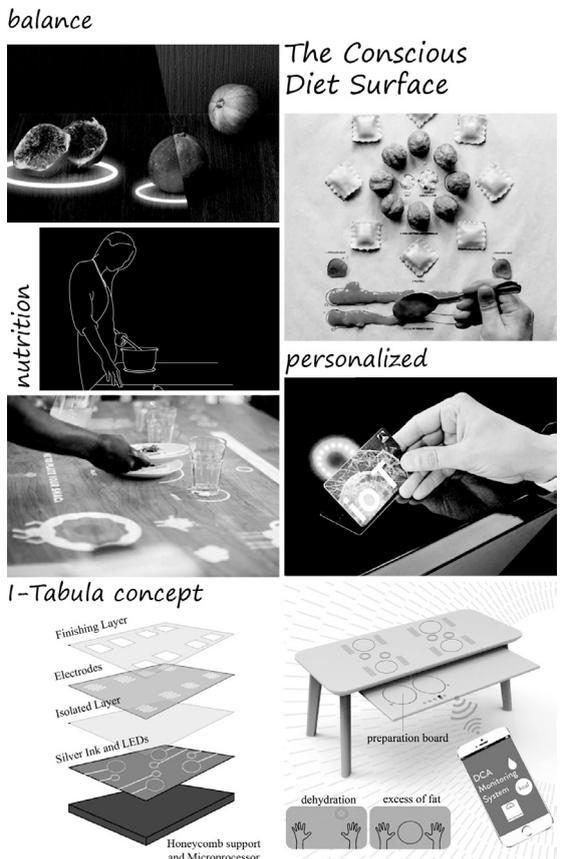


Fig. 4 - Conscious Diet Surface Scenario

pending on the user's health state and diet information. It supports the person in the right meal choice evaluating a suitable match of ingredients, using a light, and others signals languages to stop the meal.

The third scenario is "The Home Breath", based on a comfort experience at home, where USs of wood, or other conventional materials, is augmented with an intelligent system, able to monitor the interior environmental conditions and accordingly reacts. The surface can change shape to increase the interior ventilation, temperature, and light, and increase communication among different spaces. Its shape and color change informing the users about the air conditions in the interior space. The surface can detect substances floating in the air and shows their presence and the direction from which they are coming. It can detect a variety of air pollutants showing their concentration. The surface can also be used to create customized environmental atmospheres for convivial moments producing a sequence of calibrated released light effects and aromatic essences.

The fourth scenario is "Play Sense Vividness", a sensory perception amplifier. It gives a playful experience, engaging users in an augmented multisensory interaction that stimulates two or more sensory channels simultaneously (cross-modality). The experience related can more in-depth catch attention with effects in the learning and neurally-inspired experience. The surface can surprise with colorful and whetting soft, rough textures, vibration, sound, smell, and other stimuli. The feedback on the surface can be immersive.

Based on this scenario, the "PlaySense" concept deals with issues concerning visually impaired children, that in line with Maria Montessori inspired practices, encourage a deeper multisensory, through the mainly tactile and acoustic approach. A system of an interactive and playful wall of laminated surfaces is activated by touch. Thanks to a slightly rough texture 3D printed, it stimulates curiosity, energizes, and excites responding with sound and vibration feedback. The panel can be programmed to carry out 4 different educative games. Sounds consist of reproducing animal verses, rather than musical instruments, the narration of interactive fairy tales, or just the modulation of different vibrations. Thanks to an *Arduino* microprocessor, it was possible to create a basic circuit and a prototype where sensors turn the tactile experience also into an acoustic one.



Fig. 5 - Play Sense Vividness

5. Conclusion

If today physical and digital worlds are still separate, appearing in our life as parallel universes, in the next future, they will seamlessly merge. The Ultra Surfaces Vision enables this merging on a new manufacturing paradigm.

Touchscreens, keyboards, and mice that today work as connection points between the two parallel universes, still forcing people to act in unnatural ways, will be overcome by the USs. Thanks to the emerging development of microelectronic tech and related manufacturing processes, USs is expected to combine in a single solution edge AI, multiple sensors, and connectors directly embedded in the material surface.

Designing USs, we have the opportunity to help users to resolve current problems and satisfy their needs, making life smarter with meaningful experiences. In such a perspective, collaborating with different but complementary partner-enterprises, and providing students with inspirational settings to imagine future scenarios, play an essential role in the university. We are starting to improve approach leading together research and didactic in material sectors. We have adopted an open innovation approach to co-design with three different enterprises, according to the D-DMI methodologies, emphasizing a market evolution perspective.

We focused *Ultra Surfaces* workshop on sharing technical knowledge and value chain in industrial products as well as stimulating young designers-to-be to develop next future USs scenarios, making them generating SAE.

The design process took advantage of a cross-disciplinary approach, robust design methodologies already used in the field, and a multisensory perception exploration. We dealt the topic with the attention of disclosing a whole system of possibilities able to advance functionality as well as meanwhile enhance a highly multi-sensorial perception for users. The strength of this approach is letting design thinking be nourished by a more profound comprehension of surface soft-qualities and the body-mind process perception. Our method also focused on expanding the palette of senses' involvement while introducing the idea of emotions and judgment in line with applied Aesthetics and *Somaesthetics* (Shusterman, 2013).

Thanks to the method applied, all the participants, with no previous knowledge of USs, and SAE won the workshop challenge. The Ultra Surfaces vision was discussed and detailed in different scenarios, according to the SAE that the students wanted to embody.

Each Scenario and detailed concepts of a novel surface with different degrees of complexity, combine inactive and proactive components. The USs vision was improved during the workshop. The concepts were appreciated by the companies, and some of them are now in the feasibility evaluation stage for design development.

What opportunities does the USs vision open in terms of design innovation and user experience design?

- The USs can reduce the number of screens, buttons, and make the room more user-friendly, easy to understand and approach with natural behaviour. The human-machine interaction is coming implementing new functions and change the experiences on how we spend time in our living spaces. The smartness of surfaces impacts on user everyday live in terms of rituals new gestures, languages, and relational communication.

- The USs can increase the conversation between humans and objects or spaces in a pleasurable way. A USs, as a collaborative partner, can empower people in situations where they are unable to act or are unaware that action is possible (Rozendaal, 2016). They will detect events and transform them into SAE. Open platforms will help users to define the different events to detect and enable. Users will experience data through a user-friendly physical interface.

- USs vision benefits from new processes making technology *disappear* and materiality *bump up*. The electronics augmentation phenomenon has contradictory processes. It reduces the quantity of products physicality (by

the miniaturization of computing industries) and increases qualities of physicality, in term of the user solicitation with a rich palette of senses. This new physicality augments the social significance of materials and draws more user satisfaction. USs exploits the materials' potential, influencing the user's emotional involvement. They generate a multisensory full-body involvement. They engage users in SAE, featured by communicational resonances, semantic perception, epithetical feeling.

Following the rapid development of IoT as well as edge and fog computing, in the future, the interaction with Ultra Surfaces could happen in several products environments influencing our daily life.

Acknowledgments

I thanks my colleagues Davide Bruno (professor of industrial design), Lina Altomare (professor of materials science), Luca Metta (expert of microelectronics) Anna Cecilia Russo (Design Aesthetics fellowship) and the designers Daniela Ferrè, Chiara Pasetti, Giuseppe Salvia and Roberto Sironi, who collaborated to the workshop as members of tutors and teachers cross-disciplinary staff. A special thanks to Chiara Pasetti for helping me to finalize this essay.

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2. ICS Materials for exhibit design

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1. Exhibit design and ICS Materials

The field of exhibition design is, by its very nature, strongly connected with innovation, since the display of products, whether they are articles for sale or cultural assets, frequently entails triggering emotions and fascinating people. Digital technologies and their employment can serve to this aim, and, not by chance, exhibition designers largely rely on their potentials to foster engaging and meaningful user experiences.

Our reflection is here focused on that branch of exhibit design that pertains the creation of permanent or temporary exhibitions for cultural spaces such as museums, namely institutions with a long-lasting tradition of employment of digital technologies.

Since the introduction of digital technologies, indeed, museums have always been privileged venues for experimentation (Parry, 2008), given their unique ability to create a safe and controlled space where the environment, the assets and people are part of the same ecosystem.

Today's museums are largely technology supported if not technology sustained, since digital technologies are permeating most of the functions both in the backstage – digitalization, inventory, etc. – and in the frontstage – exhibits, cultural interpretation, education etc. Ranging from passive display of contents through video-walls and projectors to interactive immersive environments, from traditional audio guides (Proctor, 2011) to mixed reality enhanced glasses, museums offer a thorough set of case studies on the use of these technologies.

Nevertheless, common critiques to the employment of digital technologies in cultural contexts underline (i) the detachment of the technological devices from the environment and consequently (ii) possible distraction from the objects on show towards the devices themselves (Spallazzo, 2012).

Moving from this assumption, we explore here the potentials of Interactive, Connected and Smart Materials – ICS Materials – in the exhibit design field, envisioning future applications able to shorten or even to bridge the distance between atoms and bits (Ishii & Ullmer, 1997) and trigger novel user experiences.

We intend ICS Material as «hybrid material systems that work by establishing interactions among their constituting components, and with people, objects, and environments, through the combined use of electronic, chemical, mechanical, and biological components» (Parisi et al., 2018, p. 2).

In other words, the category of ICS Materials encompasses materials that are: (i) able to establish a two-way exchange of information with human or non-human entities; (ii) linked to another entity or an external source, not only through the internet and digital network; (iii) able to respond contextually and reversibly to external stimuli, by changing their properties and qualities; (iv) programmable, not only through software (Parisi et al., 2018; Rognoli et al., 2016).

As a matter of fact, this novel category of materials, able to merge digital capabilities in the material itself, can introduce a disruptive innovation in the exhibition design field, as well as in other design branches. However, as far as we know, no experimentations have been undertaken yet, considering that these materials are often in their PoC phase and still not ready to be massively employed.

Accordingly, in the following we speculate on ICS Materials as main building material for exhibit designers, envisioning opportunities in the field and exploring three design dimensions: namely the exhibition space, the assets and what it pertains to them, and ultimately the visitors.

2. First design dimension: the exhibition space

The first reflection here advanced regards the exhibition space, intended as that space made of walls, floor and ceiling wherein the exhibition takes place.

Going far beyond the concept of *white cube* (O’Doherty, 1999), contemporary interiors of museums and exhibition spaces are increasingly becoming interactive spaces, where the architectural elements as well as the furnishing may be enhanced through digital technologies and acquire new functions and meanings. As a matter of fact, the interpretation of museum spaces as a scenography (Atelier Brückner, 2011) where a narration takes place (Dernie, 2006), implies considering all the elements that constitute the space as a unique and interconnected system, a techno-drama (Cirifino et al.,

2011). Accordingly, digital technologies are increasingly being used as an integral part of the exhibition space, pervading walls, floor and ceiling and are no more only relegated to interactive devices (e.g. smartphones, interactive kiosks) at the service of visitors.

The ArtLens Wall at the Denver Art Museum is a renowned example in this sense. Designed by Local Projects as a tiled 12-meters-long interactive wall, it stands as the biggest one in a museum and transforms a wall into a digital repository for about 4.500 artworks that can be explored.

Other times, projections transform both walls and floor into interactive areas for visitors, as it happens in the *Time Machine* experience at the Wu Kingdom Helv Relics Museum in Wuxi, China by Acciona. Here the walls are transformed into the scenography of an evolving story, while the floor becomes a place where visitors can interact with digital objects, animals and natural elements. Further increasing the level of immersion, the Mori Building Digital Art Museum in Tokio, proposes a virtuous combination between physical installations and dynamic digital artworks able to change according to visitors' behavior and to influence each other.

The three examples listed above, show the ever-increasing tendency to permeate all the museums spaces with digital technologies/content and can be pointed as representative cases for the innovative use of traditional digital technologies commonly employed in the field, such as touchscreens and interactive projectors.

The devices act as mediators of the interaction between the users/visitors and the cultural contents – be them physical or digital – while the exhibit space, with its materiality, acts as a passive setting.

Moving from ICS materials standpoint, we may envision different scenarios, where the potential of digital technology is directly embedded into the material that constitutes the space, hence enabling different expressive opportunities.

The walls, instead of being flat surfaces on which to hang artworks and interactive screens or to project digital contents may become interfaces themselves, able to couple input and output. Looking at the field of Organic User Interfaces – OUIs – they can become «non-planar interfaces taking any 3D shape and morphing either actively or passively, to support direct physical interaction» (Nabil et al., p. 89).

We could imagine creating reconfigurable self-organizing smart walls (Farrow et al., 2013) able to modify their appearance according to people' interaction or following a complex scenography. Interior walls can also be non-flat living walls (Buechley et al., 2010), integrating circuitry into the graphics of a wallpaper and consequently able to modify its appearance in real time according to visitors' explicit or implicit interaction.

Shape-memory alloys and dynamic textiles as the BioLogic Fabric developed at the MIT (Yao et al., 2015) may be used to create shape changing surfaces, able to respond to external stimuli (heat and humidity respectively) and modify their appearance and ultimately functioning. The ceiling and the walls can open/close according to the temperature and humidity to maintain the environmental comfort or to allow/deny transparencies or create performative lighting scenarios.

ICS materials could also serve to transform the museum surfaces into a space of memory, able to keep track of each visitor and her/his interaction. Making reference to the concept of traces as evidences of material engagement (Giaccardi et al., 2014; Robbins et al., 2016), walls and floor can be empowered by ICS materials to be at the same time interfaces for visitors, triggering storytelling and interpretation, but also act at a socio-cultural level, by recording «where people, practices, and the materials of the technology intersect» (Robbins et al., 2016, p. 3).

3. Second design dimension: the cultural assets

The environment is just one of the elements constituting an exhibition space, that can serve to valorize and enhance the key contents of a museum, namely the assets it holds and displays, and their connected values.

Far from being mere objects to contemplate and not to touch, museum assets are interpreted today as triggers of multifaceted stories, often activated through digital technologies, and even valorized for their materiality (Dudley, 2009)

The traditional display of objects behind thick protective glasses with small or even non-existent interpretive labels is giving way on the one hand to technology supported solutions able to multiply the cultural interpretation and, on the other hand, to a more direct relation between assets – or their copy – and visitors.

An innovative project following the first strand is Collider Case, an interactive showcase able to superimpose images, animations and texts on the objects, by exploiting the transparent flat surface of the showcase, holographic solutions and projections.

Looking at the ICS materials field, similar – even if not comparable – results, can be achieved with low-tech solutions, by exploiting the chemical properties of materials that react to the current flow. Electroluminescent and electrochromic inks (Österholm et al., 2016), for example, can easily turn a transparent panel into a space for labels. Different graphics/texts can be

made visible on the same panel only when required, to let visitors follow a story, or simply to match their language.

Therefore, the potential of ICS materials can be exploited to enhance the interpretation of the objects on show, but it can also be at the basis of experiences based on the tangible interaction paradigm (Hornecker & Buur, 2006).

As a matter of fact, one of the last trends in the field of digital enhanced exhibition design sees technological solutions that allow for a fuller integration between the technology, the materiality of the objects and the physicality of the visit experience (Bannon et al., 2005; Petrelli et al., 2013).

Made popular in the Human Computer Interaction field after the publication of the book *Where the action is* (Dourish, 2001), tangible interaction grew in popularity together with an increasing interest in the materiality of the visit experience shown in museum studies (Chatterjee, 2008; Dudley, 2012; Pye, 2008). Accordingly, since the first decade of the new millennium, projects based on this paradigm emerged (Bannon et al., 2005) and count today several applications (Duranti, 2017).

In 2007, the VIRTEX presentation method, by Daniel Pletinckx, for example, employed a bigger 3D-printed replica of a small ivory cross embedded with a gyroscope that allowed users to move a 3D model by actually manipulating and rotating the replica.

Other times, visitors are asked to interact with a realistic replica. It is the case of the Drinking symposium installation at the Allard Pierson Museum of Amsterdam. Here, visitors are involved in a simulated drinking symposium in the Ancient Greece and must perform a libation with a replica of a Greek drinking bowl (*kylix*) or lay on a daybed. Both the *kylix* and the daybed are embedded with sensors and modify the state of a virtual world when activated: by lifting the *kylix*, visitors animate a virtual character that lifts his *kylix*, toasts and drink wine, while other actions follow those of the visitors.

Clearly, the two projects described above, introduce a completely novel way of triggering digital interpretive contents in a museum, by avoiding the traditional Graphical User Interfaces in favor of a direct interaction with physical objects, namely employing Tangible User Interfaces. The next step of evolution we foresee here by employing ICS materials is that imagined by Hiroshi Ishii and colleagues at the MIT media lab in 2012, by theorizing the radical atoms (Ishii et al., 2012). The authors hypothesize the interaction with dynamic materials, in which all digital information has physical manifestation so that people can interact directly with it. If the hypothetical «digital clay» referred to by the authors can be somehow too radical as an interface for the museum field, we can imagine coupling input and most of the outputs in the same manipulable asset. A replica covered with smart textiles (Nilsson

et al., 2011), for example, can react to visitors touch by highlighting details on the object itself and triggering a coherent audio description. Instead of using capacitive sensors and led lights, the same result can be achieved with programmable textiles, just to name a renowned example.

4. Third design dimension: the visitors

The third element composing the exhibition design ecosystem, as described at the beginning of the chapter, is the visitor. Evidently, visitors are the main addressees of the solutions/projects discussed till now, but the focus here is on the personal devices commonly employed in an exhibition space and on scenarios of future applications enabled by ICS materials.

Ranging from traditional audioguides to the most advanced augmented reality mobile apps, the panorama of cultural interpretation supported by technology is still dominated by the same paradigm: location-aware display of contents triggered more or less voluntarily by visitors through a device (Spallazzo, 2012). A long-lasting story, considering that the first audioguide was introduced at the Stedelijk Museum of Amsterdam in 1952 (Tallon, 2008) and that multimedia guides in cultural field date back to 1994, with the project iGo, developed for the Minneapolis Institute of Art (Damala, 2009).

Contemporary solutions are mostly based on mobile apps following the Bring Your Own Device – BYOD – business model, exploiting personal visitors' smartphones to trigger interpretive experiences, activated at specific locations or along the entire visit experience (Proctor, 2011). Likewise, wearable technologies, such as the smart glasses for mixed reality, are getting grip even if they are still immature and not so diffused. Examples such as the Keith Haring exhibition augmented with smart glasses at the San Francisco's De Young Museum in 2014, are now spreading.

Analyzing the evolution briefly traced above, that moves from public devices, such as audioguides, to personal smartphones, and finally to wearable systems, we could imagine that in the next future museums will invest on the visitors' body as trigger of cultural interpretation.

Looking at ICS materials, systems such as the DuoSkin by MIT Media Lab and Microsoft Research can play a relevant role in transferring controls directly to the human body. DuoSkin is a tattoo interface made of gold metal leaf able to sense touch inputs, to display outputs thanks to thermochromic ink, and allows wireless communication (Kao, Holz, Roseway, Calvo, & Schmandt, 2016). The controls, normally performed on the mobile screens,

may be done on a tattoo that visitors may receive at the ticket desk, potentially aware of their language and preferences.

We could also imagine making the devices completely disappear and merge all the scenarios envisioned in the previous paragraphs to create a unique dynamic exhibition space able to respond to visitors' bodily movements and gestures.

As a matter of fact, the paradigm of embodied interaction (Taylor et al., 2015), that transforms the human body into the main controlling device can be coupled with the potential of ICS materials to create what we can call an organic exhibition space. Organic, since (i) it can modify its shape and functions according to diverse inputs over time, (ii) it is innervated by a network that connects every element, and (iii) it demonstrates smartness in its ability to match visitors' needs and will.

5. Final remarks

The scenarios of employment of ICS materials as well as the vision about an organic exhibition space advanced in the chapter are, in great part, far to be achieved and mostly relying on materials and solutions in their PoC phase.

Nevertheless, they can be interpreted as a glimpse from a future that is near, from a technological point of view, but requires a radical change in the way of thinking interactivity in museums.

Despite the contemporary work of the most renowned exhibition designers tries to seamlessly integrate digital technology in the exhibition space and make it disappear to trigger a memorable user experience, the relation between technological devices and the ecosystem made of space, assets and visitors is still seamful. The interaction, indeed, is still relying on input given through devices and separated outputs that may favor detachment and distraction from the assets on show, as pointed at the beginning of the chapter.

The exhibition designer of the near future will need to follow a logic of integration, by imagining interaction both at the micro and macro level. Imagining the integration between atoms and bits at the atomic level (Ishii et al., 2012) or at the level of computational composites (Vallgård & Redström, 2007), indeed, means profoundly modifying the way we imagine interaction and design for it.

ICS materials are paving the way towards a holistic view of interaction, in which every element is connected to the others, and its able to modify itself in a continuous process of adaptation and evolution. In this sense, designers must think of the exhibition space as an ever-changing organism.

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3. Smart Products & ICS Materials

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In this chapter, we use the term smart with a slightly different meaning, this time not referred to smart materials, but to smart products that incorporate IT technologies. The objective of this chapter is twofold: first, we want to give an overview of the concept of product smartness and smart products, then we reflect on the relationship between smart product and ICS materials.

While smart products are a product category that represents networked consumer electronics, the concept of product smartness is broader and defined by two main dimensions, one more technical, and the other more linked with user perception.

This chapter is an opportunity to reflect on the role of ICS materials -materials that are advanced, interactive and technological - in the development and design of smart connected products.

This arises important questions such as: do smart products embed smart materials and ICS materials? What are the limits and opportunities for their application?

The considerations in this chapter come from the authors' professional and academic research, which deals with the design of meaningful smart products and of conversational products, envisioning possible new opportunities and potential threats.

Keywords: Smart Products, ICS materials, Smartness

1. The concept of Smartness

The term “Smart” has multiple meanings and can be referred to people, materials, devices, systems and more.

A material is smart or intelligent/responsive when one or more of its properties can be controlled and significantly changed in a reversible way (Spaggiari et al., 2019). Then, when a product can be defined as smart?

Generally, the term is used to identify those products that become intelligent through embedded processing capabilities and the use of IT technologies.

Smart products are a product category that represents internet-connected consumer electronics that embed computational intelligence. Other terms such as intelligent products, connected products or smart things have been used to describe the same concept (Kiritsis, 2011) and refer to various technological paradigms such as Internet of Things, Ambient Intelligence (Aarts & De Ruyter, 2009), Ubiquitous Computing and Pervasive computing.

While an agreed univocal definition of “smart product” does not exist, it is possible to identify which are the characteristics that these types of products should have to be named “smart”.

The concept of product smartness has two principal dimensions: the first one is the technical dimension, in which we find technical specifications or requirements that the product should have; the second one is the perceptive dimension, in which can be identified those characteristics that users perceive as smart (Rijsdijk & Hultink, 2009).

2. Technical dimension of product smartness

There are different definitions of “smart products”. They can be defined as those objects that can use information about themselves and about the environment in which they run, and that can interoperate with other products (Gutierrez et al., 2013).

From a more technical point of view, they can be defined as products with embedded IT technologies, generally connected to other devices or networks, and with incorporated microprocessors, sensors and actuators, in order to obtain some benefits for the end-user: control over the performance, enhanced product features, function and capabilities (Dhebar, 1996).

There are three common characteristics that smart products share: they are cyber-physical, networked and embed computational intelligence (Vitali & Arquilla, 2019).

Smart products are **cyber-physical** (Abramovici, 2014), or **phygital** because they blend hardware and software. They are physical objects with digital representation, and interaction can occur through multiple, multimodal interfaces.

Smart products are **networked** and part of a larger network of things, people and services. Connectivity enables them to communicate with users and other objects, and can happen in different forms: one-to-one connection, one-to-many, many-to-many (Porter & Heppelmann, 2014).

Smart products **embed computational intelligence** and display forms of autonomous and proactive behaviours (Gutierrez et al., 2014; Rijdsdijk & Hultink, 2009; Abramovici, 2014; Maass, Filler & Janzen, 2007; Mühlhäuser, 2017). Computational intelligence enables them to be context-aware, perceiving information about its use and environment, adapting and personalizing their behaviour. They are more proactive and can anticipate the user's intentions (Maass et al., 2007).

Connectivity and computational intelligence allow data to be exchanged between different products and enables some of their functions to exist outside the physical device (Maass et al., 2007) such as monitoring the product's conditions, its external environment, and its operations and usage; control various functions as well as to personalize the user experience.

As already mentioned, the other dimension of smartness beyond the technical aspects is the perceptive dimension: what people perceive as smart?

3. Perceptive dimension of product smartness

The smartness of a product perceived by a user is described as a construct of seven dimensions identified by Rijdsdijk & Hultink (2009).

These dimensions are: autonomy, adaptability, reactivity, multi-functionality, ability to cooperate, human-like interaction and personality.

Smart products usually possess one or more of these dimensions. However, these functionalities must be obtained using Information Technologies (IT) for the product to be described as “smart”. The degree of smartness depends on the degree they possess these different dimensions, and with what extent (low, medium, high).

Autonomy is possessed by those products that can, to a certain extent, operate independently without the need for user intervention.

Adaptability and reactivity are two similar but different concepts. A reactive product can directly respond to stimuli; for example, it perceives a change in the environment through a sensor and signals the users. An adaptive one, can react and adapt behaviors over time: for example, a screen with adaptive brightness reacts to the light but also remembers what are the user's preferences in that situation.

Multifunctionality is another quality that users perceive as smart: products that can perform multiple functions are seen as smarter and more advanced. So are products that can cooperate and are compatible with other services and devices. Compatibility is a crucial characteristic for networked products, since being part of an ecosystem makes them more competitive in the market (Agrò, 2018).

In the research of Rijdsdijk & Hultink also emerged that products that re-create a humanlike interaction and have a personality are perceived as smarter. For humanlike interaction, they refer to the degree to which a product can communicate and interact in a human-friendly, natural way. Personality instead refers to the smart product's ability to possess a credible character, with believable personality and emotional state. This is particularly evident in products that embed conversational user interfaces (CUI), such as virtual assistants (VPA) like Alexa and Google Assistant (Vitali & Arquilla, 2019).

4. Smart products and ICS Materials

Materiality impacts the experience with products. The interest to develop a new generation of interactive materials to produce smart products is arising, and those interactive materials can be identified as ICS materials (Parisi et al., 2018 A/B).

ICS is an acronym for Interactive, Connected and Smart materials, and identifies those materials that, by operating new and complex functions, can provide an interactive, connective and smart material experience (Ferrara et al., 2018). ICS materials can “feel” and react to external stimuli with specific behaviours. They can be defined as composite entities in which artificial intelligence and materiality are combined (Ferrara et al., 2018).

ICS materials are characterized by the reciprocity of action and reaction with users/environments; variability of properties so that the reaction is reversible and contextual; they can be programmed (not only via software) and connected to establish a two-way exchange data (not only via network). These characteristics can be achieved through electronic, chemical, mechanical and biological means.

An ICS Material is not necessarily an original material that integrates all the features described in the definition (Ferrara et al., 2018), but it can be considered akin to a technological component with programmable behaviour.

Materials have different degrees of smartness. Parisi et al. (2018-B) propose a map for ICS materials that consider their degree of interactivity, smartness and complexity, and divides materials in inactive, reactive and proacti-

ve materials. Reactive materials include smart materials that can reversibly change features in response to specific stimuli.

Proactive materials are closer to the concept of ICS materials: represent a combination of inactive or reactive materials with embedded electronic components in the form of sensors and actuators, connected with external or embedded computers.

Despite the technological availability and the increased range of interactive materials, their possible applications in electronic goods are still to be fully understood (Coelho et al., 2009; Parisi et al., 2018-A; Razzaque et al., 2013; Vallgård et al., 2016). Examples on a wide scale are missing, so there is still space to reflect on ICS materials and their applications.

5. Are Smart products using ICS Materials?

Looking at the consumer electronics market, it is possible to categorize smart products into three macro-categories (Vitali, Arquilla & Rifino, 2019).

1. In the first case, the smart product is the technological and connected version of an existing analogue artefact. For example, a smart vase that can monitor a plant's needs and water level.

2. In the second case, the object is defined smart because it is a more advanced, connected version of an existing electronic/digital product. For example, a smart washing machine that can be controlled through an application.

3. In the last case, the object is smart because it is a combination of new and existing functions that create a new product category. An example is the Roomba vacuum cleaner, that combines robotics and vacuum cleaning.

All these products are considered smart for their technological performance, and because they embed electronics components and IT technologies.

As previously said, in the consumer electronics market, the suffix “smart” is used in close relationship with technology, rather than for the use of smart materials. It is rare to see a technological product defined as smart because it uses smart material.

For example, if we think of a “smart bottle”, we would probably imagine a product that quantifies how much water is consumed, or that can change or maintain a set temperature, or that processes the liquid inside. Therefore, it would be considered smart because of its technological value. In the consumer market, a bottle that uses an advanced super-hydrophobic nano-coating to let the liquid inside slide without sticking to the surface wouldn't probably be defined as a smart product.

Currently, it is hard to say that smart products embed ICS materials. This because it may not be easy to differentiate between an ICS material and a standard electronic component embedded in a material.

For example, let's imagine a smart product that integrates a touch display or capacitive sensor, hidden behind a material so that it seems embedded in the surface. The result will be interactive, yet with specific limited dimensions, and the different components are not fused in a material, they maintain their materiality. Is it considered an ICS material?

The boundary between electronic components and ICS material is not clearly defined.

Moreover, it may be possible that ICS materials are used in a product, but it is not evident to the final consumer because they provide a feature that is not visible.

One example is when a product embeds in-mould electronics (Fig. 1). With in-mould electronics, a flexible circuit is encapsulated in an injection-moulded plastic part. This part could be used for control panels and interactive controls for appliances and broad surfaces such as automobile control panels.

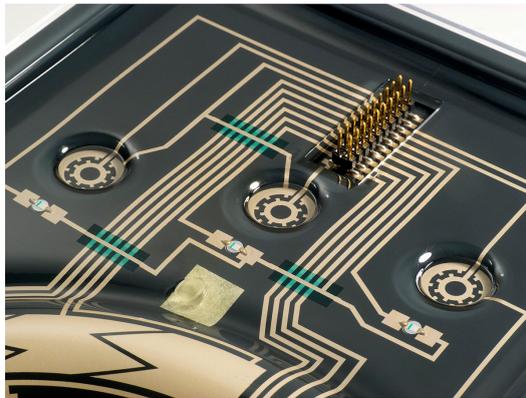


Fig. 1 - Example of in-mould electronic by DuPont, TactoTek <https://www.designnews.com/thermoforming/duPont-tactotek-ratchet-mold-electronics-efforts/176641071057057>

This technology, and printed circuits in general, enable to produce compact products, with less thickness and dimensions.

Their use can have an impact on the shape of the product but may not affect the experience of the end-user.

This may be different in the case of wearables and products that have to be worn on the body. In this situation, printing the circuit on a flexible

media, or relying on sensors infused in textiles or other media can positively improve user comfort.

6. Limits and opportunities of ICS materials for Smart products

Previously we discussed about Smartness and Smart products; we briefly defined what ICS materials are and made considerations on their applications in the consumer market. This section reflects on what are possible limits and opportunities of ICS materials for smart products. It mainly focuses on manufacturing, upgradeability, and scale of application.

Launching a smart product on the market is an action with a significant impact on a company (Porter & Heppelmann 2014). This because smart products follow a development that is more similar to software than hardware. A smart product has to be updated in time and needs to be supported by a reliable infrastructure, both in terms of technology and service providing.

The smart product uses different technologies such as hardware, software, communications, and cloud platforms/applications.

The manufacturing phase is a crucial moment in their development. To be economically feasible, they employ mass-produced, standardized components to limit the manufacturing price. This is a barrier to the use of more innovative materials and components: if a company doesn't have a structure to support the development of innovative technology, it has to rely on more standard parts.

Smart materials and more advanced ICS materials are often deepened in experimental studies or research products. This is a limit for a broader application in products for the consumer market.

Until those material doesn't become more standardized and available, not all companies could access them.

What are their technical characteristics? How do they enter in the existing production chain? How much do they cost? What are the benefits compared to a more standard component?

These are all questions that need to be strategically evaluated because innovating involves risks. In particular, innovative materials should guarantee lasting, reproducible, and controlled performance over time.

Curved smartphone screens are an example of the risks of innovating through ICS materials. Samsung was the first to launch on the market a smartphone with a foldable screen, but unfortunately, the first version had to be withdrawn from the market. This because the screen had structural problems

and was easily worn or damaged, also because the beta users were convinced that they had to remove a film that was instead part of the screen structure (Fig. 2).



Fig. 2 - Samsung curved screen, damaged. <https://www.businessinsider.com/samsung-galaxy-fold-mess-explained-2019-4?IR=T#6-but-just-days-later-review-units-started-failing-for-a-variety-of-different-reasons-6>

For a brand, developing a proprietary ICS material may be a strategic move to be competitive and recognizable on the market.

For example, LG invested in flexible OLED panels and produces them also for custom applications. In this way, the ICS material becomes standardized and cost-effective, thus desirable for consumer electronics producers.

Upgradeability is another limit to the use of ICS materials for smart products. Smart products are “never closed”, and they can be updated during their whole life cycle. Through software updates, an existing connected product can offer new functionalities to its users.

Even though the digital/software component is relatively easy to upgrade, the hardware component represents a harder challenge, because it is not easy to remove and modify after the product purchase.

The problem of obsolescence between the hardware and software components shortens the life cycle of the product. For instance, a working smart product that has compatibility issues and that doesn't support your smartphone anymore, suddenly becomes “old”, and its life cycle ends. This situation may also depend from the use of obsolete hardware components. Therefore, if we embed electronic components in artefacts that have a longer life cycle, such as furniture, we need to consider the problem of obsolescence from the start, designing for upgradability.

One good example was Nest, the smart thermostat now produced by Google: when was launched on the market it embedded some sensors that weren't even connected and used. This because they were activated later in time, in another update, to provide new functionality.

Using IT and interactive components that are embedded in materials can provide a challenge to tackle the problem of hardware/software upgradeability and obsolescence.

ICS materials can represent a good opportunity in specific scales of applications, especially for extra-small and extra-big formats.

On a traditional medium-to-small scale there are numerous standard components or strategies that can be used to exchange information, communicate, interact etc. For example, a LED that transmits feedbacks, a cap sense to make a capacitive button, are all standard components available at a low price and easy to control.

However, those components may have technical limits in case of miniaturization, and of economic limitations in case of bigger sizes of application. Therefore, ICS materials could be an exciting opportunity where conventional electronic solutions are not effective.

Technology infused in materials can bring to a significant reduction in product size, and open to new possibilities, mainly if they can operate without the need for batteries. One interesting example are debit cards that embed fingerprint sensors to authorize payment.

At the same time, ICS materials could be useful in other formats such as at the architectural level, to build interactive solutions that are more economically feasible and sustainable.

7. Conclusions

This chapter collects initial reflections on the relationship between smart products and ICS materials. After analyzing the concept of smartness and intelligent products, we include considerations on the possible limits and opportunities of the application of ICS materials.

Further clarifications need to be made to define more clearly what are the boundaries between ICS materials and embedded technological components. Interactive, Connected, Smart materials are an opportunity that needs to be formalized for a widespread application in the consumer electronics sector. They are still in the experimental stage, and their real availability is often still far enough from the actual market. When developed, they can become strategic elements to increase brand recognition and reputation.

Manufacturing and standardization in specific production chains is probably their hardest challenge, while they offer interesting opportunities in extra-small and extra-large scales of applications.

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4. ICS Materials as new frontier for Wearable technologies

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1. Wearable Device: potentialities and challenges

The development of new technologies has been having a huge impact on daily products and systems in term of aesthetic and performances. In particular, the recent interest in wearable electronics, human/machine interfaces, and soft robotics, among other areas, has brought an entirely *new class of electronic devices – known as “stretchable electronics”* (Muth et al., 2014). The electronic industry is indeed in the middle of a paradigm shift: novel possibilities are emerging, ranging from limited flexibility to comfortable electronics. This transfiguration has been visible for more than a decade now, but it has not made substantial impact on commercial products yet, especially when it comes to textile integrated sensors for wearables.

The term “wearables” refer to two categories of products: (1) Devices: Discrete electronic hardware mounted on objects designed to be “worn” (e.g. glasses, headgear, footwear, skin patches, handbags); (2) Apparel & textiles: smart garments featuring integral or distributed electronics used to manufacture a final object (e.g. clothing, rucksacks, bandages).



Fig. 1 - Examples of Wearables

Despite some evidence, wearable technology is still in its infancy: for the industry to reach its full potential, there is the need for materials and embedded sensors to be lighter and more flexible. Due to the disparate me-

chanical properties of soft materials and conventional rigid electronics, so far integrating electronic devices within highly stretchable matrices has proven difficult. Soft sensors are typically composed of a deformable conducting material patterned onto, attached to, or encapsulated within an inactive stretchable material. To create the desired sensing geometry, a number of processing methods have been employed to date, including lithographic, planar printing, coating, and micro-channel molding, filling, and lamination techniques. While these methods are effective at creating sensors, problems such as limited extensibility, high cost, poor durability, or lack of manufacturing scalability have prevented their widespread adoption. As a result, nowadays on the market there are few products that are truly mobile and wearable and accomplish a full integration of design, comfort and performance. We can affirm that smartwatches and fitness trackers are, up to now, the only wearables. This is bound to change in next years as *advances in technology will allow for unobtrusive integration of electronics in ordinary objects and textiles.*

To face the challenge for wearables to reach their full potentiality, application and development there is a need of hybrid, layered materials. In here the connection between wearable technologies and a new class of materials called ICS Materials is explored. ICS Materials (Interactive Connected Smart Materials) are defined as systems combining inactive materials, stimuli-responsive smart materials, and embedded sensing, computing, and actuating micro-technologies. (Parisi et al., 2018)

They are material-based systems with different degrees of complexity combining inactive materials, smart material components, and embedded sensing, computing, and actuating technologies.

They arise as potential solutions to fulfill wearable functionalities and to be enablers of meaningful dynamic and interactive experiences as tangible interfaces in wearable devices domain.

Indeed, while designing wearable technologies a designer/professional needs to take into account to main issues: functionality of the system (sensor, materials, actuators) and user needs (acceptability, perception, wearability).

2. The Design perspective

Wireless wearable communication is a field of increasing research interest due to the numerous potentials offered in areas such as healthcare and fitness monitoring, mobile network/internet and functional clothesto name a few.

The huge impact of emerging technologies has been changing population's capabilities (physical, sensorial and cognitive) and lifestyle (works, leisure, living and social interaction).

Currently there is a great inclination to modify sport and well-being concept by changing the technology in "wearable". Wearable technology represents a potentially large and rapidly increasing research and development area, involving several cross-disciplines such as, micro-nanotechnologies and material sciences, industrial sectors like medical devices, electronics, microchips, textile, telecommunications and engineering disciplines. Such devices can perform functions such as sensing, communications, navigation, decision-making or actuation.

Wearables refer to a class of devices really integrated in daily life, used all the time, wherever the user goes. A wearable product needs to both work and look good and be worn in the same way the user wear clothing in order to achieve the paradigm *anytime, anyplace, by anyone* (Marculescu, 2003). Although there is a wide range of commercial wearable devices there are few products, which truly become "mobile" and accomplish end-user really need.

The expression **wearable** refers to electrical or mechanical systems, which are worn on the human body by means of incorporation into items of clothing, or as an additional apparatus, which is fixed, by straps or harnesses.

This kind of device is made up of "wearable" sensors. Wearable sensors and systems are defined, as wearable sensors/actuators and sensor-based communicative systems that can monitor and/or stimulate, and/or treat, and/or replace biophysical human functions.

Due to the intimate interaction between technologies and human body, the mobile electronic devices have created the potential for wearable technologies which are mostly embedded into garments or accessories that function constantly and are worn comfortably on the body. Although wearable technologies are seen as solutions to create a more comfortable usage of technology, the designers, materials expert and companies should approach embedded technologies on human body in different levels which are functional, physical and emotional.

As with any innovative technology and product development, there are challenges associated with bringing wearables to the market. "The human body shape is curvilinear, but the conventional electronics are flat" (Dr. Huang, Professor of mechanical engineering, civil and environmental engineering, and materials science and engineering at Northwestern University).

Among all the several challenges we might certainly list:

- **The Miniaturization:** Limited size and thickness requirements for components in wearable devices, smaller components -more design flexibility, ability to make technology invisible.

- **The Flexibility:** Flexible mobiles and increasing integration into all wearables/ e-textiles increase requirements for flexing/stretching. The vision behind wearable computing foresees future electronic systems to be an integral part of our everyday outfits. In twenty years, many applications have been explored in fitness, healthcare, military, automotive areas but the original and still good target for wearables is in some way ubiquity: these electronic devices have to meet special requirements concerning wearability, usability and need to be washable. Wearable systems will be characterized by their ability to automatically recognize the activity and the behavioral status of their own user as well as of the situation around them, and accordingly to use this information to change and modify the system. The first step to reach the target of ubiquitous intelligent textiles is the study on smart materials. In a second phase, it is to be considered in which way these smart materials can be processed into a textile and fully programmed.

3. When ICS Materials meet Wearables

Till now the research allowed for a whole range of smart textiles but sometimes the commercial output is represented by garments that contain conventional cables, miniaturized electronic components and special connectors. As humans prefer to wear comfortable textiles rather than hard, rigid boxes, first efforts have been made to use the textiles themselves for electronic function. So, we can say that the limits at the moment are: (i) **Comfort and design**; (ii) **Usability**: mainly due to the way the materials and sensors are shaped.

Steve Mann, one of the founding members of the Wearable Computers group in the Media Lab and considered the father of wearables, defines wearable computing as “the act of wearing a computer on the bodies”. A wearable computer is defined as a “fully functional, self-powered, self-contained computer that is worn on the body [and] provides access to information, and interaction with information, anywhere and at any time” (Barfield & Caudell, 2001).

The development of a wearable needs than to work properly and to be pleasant and acceptable.

To do so, a designer needs to deeply look the relationship between a wearable and the body, addressing the implications of anatomical features shape, physiology and psychological impact wearables have when designing for the end-user’s needs.

A designer has to understand how to shape technology in a desirable way for the users and the real meaning of the “*comfort*”. Designing a wearable system needs to find inspiration from the human body, in respect of the many ways that *form follows the function*.

Designer’s objective is to achieve an “*anatomically correct design*”; this implies a study on placing objects on the human body with regards to mass, size, shape, mechanical properties. The reason of this is visible in the lately technological developments: new technologies simulate body functions and strengthen the organic features. Clothing and prosthesis are instruments thanks to which body redesigns itself. This is the reason why, the wearable should be not an overlapping structure or close architecture but an enveloping film, “a second skin” aimed at meeting the so-called wearability.

Wearability literally means the right relationship between human body and the shape of worn objects and concerns the way the different shapes blend with each other. Dynamic wearability needs to be satisfied as well; this means understand the way the form of body changes with simple motion: anatomical body features need to be investigated and tests on both a mannequin and human body are suggested in order better figure out the right position and the way to shape the project.

Briefly the designer activity should benefit from gaining an overview on: (i) human physiological issues that impinge on the design of the functional product; (ii) practical issues to do with the demands of the body that may be addressed in everyday life in terms of comfort; (iii) appropriate aesthetics in relation to measurement, shape and fit, predominant posture and the ergonomics of movement; how to enhance and support the body where needed without restricting movement.

Those considerations imply the need of a layered system. According to McCann et al., (2009) this system normally comprises a moisture management ‘base-layer’ or ‘second skin’ designed to follow human body and movement, a middle insulation layer often integrating electronics, and a protective outer layer. Elements of personal protection, or body armor, may be incorporated into the system as well.

Designer has to address the real needs of the body from the outset not design for the technology then place it in a softer shell.

From the user point of view instead, the psychological ‘feel good factor’ is directly related to appearance and style as well as to the reliability, or the perception of reliability (functionality), of the wearable system.

This layered system designed to follow human shape and movements should then match the also the functionality and the smart features of wearables. Here comes the use of ICS Materials exactly framed as the layered

system into three dimensions: (i) inactive components, e.g. the substrate material; (ii) reactive components, e.g. passive substances responding to external stimuli; (iii) proactive components, e.g. computation and electronics (for further understanding refer to the chapter 2.2).

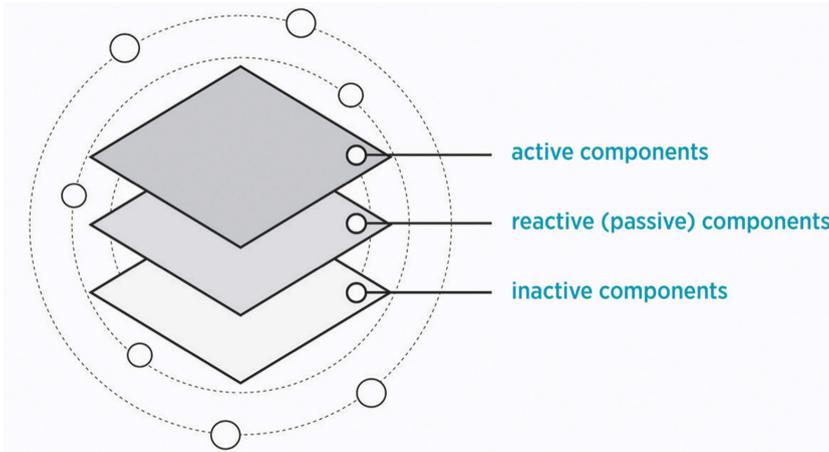


Fig. 2 - A layered ICS Material framework

In relation to the field of application the ICS Materials can be shaped accordingly, for instance when designing wearables for sport or health, the active component should contain the intelligence to detect the human parameters (i.e. e-textile with piezo sensors to detect breath) and then be the second skin. On the contrary in application such as detecting polluted environment the active component should be the outer shell.

4. Conclusion

The term Wearable Technologies is associated to those clothing and soft or hard accessories which integrate electronic components, or which are made of smart textiles.

Forms and Technologies of wearables fall mainly into two categories: soft/hard supports, soft/hard electronics.

Wearables likewise any kind of disruptive technologies change the way people behave and interact defining also the behavior of artefacts, environments and systems (Forlizzi et al., 2004). It is therefore crucial to design

them, as they uncover new modes of interaction as well as new ways to engage, entertain and inform people. This approach to applying new technologies to the real world is very much linked with the idea of designing experiences, which means to design not only functional elements (realm of engineers), but also the features needed to involve users at an emotional level.

While emerging technology is rapidly getting intimate to the human body in shape of various electronic devices, wearable technology can be a medium to facilitate the integration. The designers of the future technologies should consider the fact that human body is not a singular being but exists with its surrounding and its inner system. To bridge the gap between in and out, wearable technologies can provide solutions where technology is not any more seen as a hard cover, but as flexible displays on the human body. By giving the intelligence to our garments making them wearable, they could behave as covers which obtain an optimum behavior and increase the quality of life.

Combining user needs with social needs can bring new perspectives to the role of technology in daily life. The nature of innovation changes: the sphere of technologies and forms bends with sphere of signifies and experiences. Designer, which is a bridge between the technology and the user in order to create user-friendly interfaces, needs to consider the social, cultural and personal changes. By keeping the user in the center and doing research about social trends and how society is changing designer should be able to generate solutions not only tangible like new aesthetical look, but also focus on intangible values which are felt by experiencing. He needs to be aware of how to turn negative side effects of technology into positive ones, designing more human friendly interfaces and products.

Putting the user in the center of the design development and how to fulfill not only ergonomics issues but also user unexpressed desires to alter his emotional state in daily life. The wearable technology, the intelligent covers of the human body, may emerge as an ideal solution for various future needs which are in a continues transition by the influence of emerging technologies. This user centered experience was a kind proof that the ideas which start from the human body existing with its surrounding could give a rise to solve not only evident problems of individuals but also overlooked cases such as sensorium. The technology, which is now perceived by restricted senses, can evoke our whole sensorial system by merging with our garments, the nearest surfaces to the human body.

In this sense, the application of ICS materials into wearables unfolds many opportunities both from an aesthetic and functional perspective. ICS Materials meet both the need of a functional wearables and the one of a comfortable, designed around the body wearable.

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5. NautICS Materials: the method in practice, a workshop for Future Yacht Design

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1. Trends in yacht design

With emerging technologies and cutting-edge materials, the yachting industry is rapidly evolving. While shipyards and companies are still recovering the negative effects of the global economic crisis from 2010 and 2017, designers are moving the borders of the traditional yacht design to meet the needs of modern yacht owners. The yachting market, as well as the broader luxury landscape, is nowadays under transformation by the shifting wealth demographic. The change is marked by a move from accumulating tangible assets to pursuing rare and tailored experiences. In a world where Ultra High Net Worth individuals value experiences more than goods (C&N and Wealth-x, 2017), the yachting is moving away from the traditional preservative nature of this industry with ergonomic-based use of space and structural stability at the centre of design practice. The demand for small and medium crafts is nowadays shrinking and shifting, and the yacht market is growing both in sales volume and on boat size. The superyacht market, indeed, is continuously rising since 2014 benefit from the upward demand for yacht charter and water-based luxury experiences moving day by day towards a larger segment (Global Industry Analysts Inc, 2017; Deloitte, 2018). In 2018 the up 60 meters market segment, so-called ‘megayacht’, has grown by an average of 11% and with the perspective to reach US\$ 74.7 billion by 2022 (Boat International, 2018).

As yachts are evolving into superyachts and megayachts, the design projects are distancing themselves from the previous preference for minimalist ergonomics based on the use of space, in favour of a full sensory experience (Campolongo, 2017). This type of boat is part of what is called luxury design: the project is highly influenced by the specific culture and personali-

ty of the client and where the phenomena are revealed with such emphasized and special characters (Celaschi et al., 2015). Despite this, looking forward to the emerging yachting trends we can identify the following three key features in emerging yacht design (Bionda & Ratti, 2018).

Experience the sea

Designers are now experimenting with new soft features for higher sensory expression looking for new practices of interaction between the yacht, the sea, and human behaviour. As introduced in *The Future Yacht* by Boat International (2017): «Lifestyle design is the new undercurrent of yachting, promoted by fellow disruptors who assert that most currently available yachts don't live the way today's new affluent society does. The disconnect is palpable. People want a vessel that will give them experiences they can't have elsewhere, and for too long have been handed designs for vessels that simply replicate all their land-based elsewhere, albeit with a pointy end. These are exciting times, yachting at the cusp of change».

Aesthetic beauty assumes an important meaning as it becomes a significant catalyst of emotions: the on-board experience might throw the end-user into a daydream dimension. The factors that are marked out as desirable from owners are time for making every moment count, privacy during the experience, and personalization to provide something truly unique.

Innovative layouts

The General Arrangement is moving away from traditional yacht interior structures with divided interiors and small outdoor spaces. Nowadays, we could observe an increasing focus on larger outdoor areas and light open-plan interiors. Organic structures and pop-up spaces are explored in several yacht design concept projects. The line between indoor and outdoor is being redefined. Large open-plan saloons move and blend with outside space designed to emphasize the sense of communion with the sea. Spaces themselves are evolving with glass and material technology advancing. The structural constraints are becoming less, leading to more interesting ways of designing and combining areas.

Yacht exterior saloon and beach clubs are becoming an essential focus in yacht design pointing to convert a yacht into a sleek, floating entertainment centre. In this context, Water toys assume a primary rather than a secondary

meaning in the voyage. Superyachts often carry additional toys and tenders to cater to this need. Alongside standard ones such as jet skis, water skis, and canoes, there is an increasing demand for the latest gadgets, be it a jet-lev, skibob or hover-board. Tender and toy garages are no more a technical space but are transformed in technology beach club at direct contact with the sea.

Focus on health & wellness

Owners are looking to carry their balanced life-style into the world of yachting. The latest launches are making wellness a priority, with large relaxation areas taking centre stage (Hogarth Joneson, 2019). Onboard wellbeing extends far beyond running machines and weight sets. Spa experience is accelerating: a series of rooms combine every possible facility – infrared sauna (whose rays reportedly penetrate skin tissue more efficiently and even burn calories), hammam, Vichy water massage tables, heated marble massage tables, experience showers with multiple lights, sounds and pressures, hydrotherapy pools, plunge pools and snow rooms – and they come with their own dedicated spa manager, along with a communal space for guests to relax in, too.

Despite that, wellbeing is not only technology on board. Relaxing cocoons and underwater rooms are becoming popular as the last frontier of the physiologically pure onboard escapism.

2. ICS Materials as enablers of meaningful experiences in Yacht Design

In a sector that increasingly encourages sensory experience, the yacht design project may also be an experimental platform for interactive, connected, and smart – ICS – materials. As well as products and services, the domain of materials for design is changing under the influence of an increased technological advancement.

At this stage, ICS materials are not used in the yachting sector. Some experimental projects were done during America's Cup campaigns with optic fibres sensor embedded in composite materials to monitor composite structures or sails pressure. As argued by Ferrara and Bengisu (2013) such materials are typically not considered smart: «if the mechanism modifies the state of energy of the material but doesn't affect the material itself, in that case the reaction consists of an energy exchange from one to another. The material remains the same but the energy undergoes a change».

Contrarily, changing their characteristic on external stimuli, ICS materials could influence the aesthetics and perception of spaces encourages sensory experience. Taking inspiration from other industrial sector, yacht designers might implement a new generation of material for composite structures, exterior and interior design, and sails design with dynamic, augmented, and proactive proprieties.

On this theme, two research-through-design activities were organized and run by the authors. At first, new scenarios for yacht design were built based on the Hand-on workshop of the ICS_Materials research project (Parisi et al., 2018), then a 3-day workshop named ‘NautICS Materials’ was carried out to foresee Future Yacht design concepts by conceptualizing new ICS materials. The NautICS Material workshop was furthermore the first opportunity to test and verify the *Design for ICS Materials methodology* described in the previous chapter by Parisi and Rognoli.

3. Building scenarios for NautICS Materials

The first research-through-design activity organized on the ICS Materials for Yacht design theme was focused on exploring and building new scenarios for the implementation of Interactive Connected and Smart Material in the Yachting sector through card sorting and focus groups workshops.

As yacht design is moving the attention to the “soft” features for higher sensory expression, we chosen the Materials Experience (Karana, Pedgley, & Rognoli, 2013) as the lens to looking for new practices of interaction between yacht, sea, and human behavior in a superyacht project. In the card sorting workshop, the sensorial, emotional, meaning, and performative layers of experience (Giaccardi & Karana, 2015) of ICS_Material case studies (Parisi et al., 2018) were taken into consideration to create five overlapping groups of cards. Each cluster was described with both the reactive and proactive material characteristics and the inducted stimuli in sailing. Then, the groups were named with the stimuli triggering the material experience and detailed with keywords. Based on these first results and taking inspiration from other industrial sectors, the focus group ‘ICS4YD Workshop 2017’ (Bionda & Ratti, 2018) was performed to build different scenarios for ICS materials in the yacht design framework. Mood-board and envisioning textual storytelling were the supportive tools to present each scenario in an inspirational A4 board, the *Yachting Scenarios Boards*.

The warty jellyfish mood

Lights and sun glare reflected on the hull while sailing and mooring are bringing into the living space. Lower deck interior layout benefits from light responsive and light emitting materials, as well as from photo-luminescent and bioluminescent materials. Natural light interact with the artificial ones in an augmented reality landscape. Keywords: luminous interaction, bioluminescent, photo-luminescent, phosphorescent, electroluminescent mimics, light response, light emitting, bacteria colour changing, digital photosynthesis, glowing surface, light dimming, interactive light play.

Wave of good noise

Technical systems and engine room noise are re-shaped and synthesized waveforms change the shape of materials in order to emphasize sound of the natural elements where a yacht is placed. Sound interaction could be facilitate by gesture control and touch pad. Keywords: sound manipulator, sound instrument, sense of touch, pressure, shape-changing vibration, pin-based display, vibration sensor.

Moisture poetry

Materials with embedded bacteria as bio-actuator react to the interior heat modifying its shapes and geometry and enabling humidity to evaporate and cool down the interior temperature. Growing materials, shape memory alloys, interactive garments react to short-term environmental condition to create a new aesthetic experience. Keywords: moisture reaction, bacteria, shape changing, shape memory, layered structured, bio and growing material, biodesign, texture change.

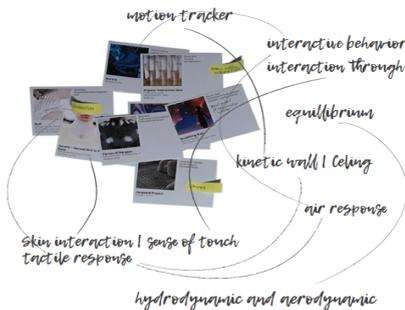
Thermo-taste

Hulls painting materials and exterior furniture materials fully modify their colour under the air or water temperature changes in their surrounding. Thermocromic materials reveal graphic patterns: at every moment everything is changing and every moment carries it's own unique aesthetic. Keywords: colour changing, thermocromic ink, tanning processes, heat responsive mate-

rials, ph water pigments, oxidation, pattern-revealing, aging material, heated garment, thermaltech, metamorphical.

Dynamic equilibrium

Materials play with the intimacy of yacht dynamics and environmental conditions. By tracking hull dynamic stability – and instability – materials translate into design the various motions engaging the yacht owner in a conversational and empathic relationship with waves currents and tides. Keywords: Skin interaction, sense of touch, sense of skin, air response, motion tracker, tactile response, kinetic wall, kinetic ceiling, interaction through gesture, aerodynamic macro-structural matrix, sight responsive materials, interactive behaviour, brain activity behaviour.



Dynamic equilibrium

Materials play with the intimacy of yacht dynamics and environmental conditions. By tracking hull dynamic stability – and instability – materials translate into design the various motions engaging the yacht owner in a conversational and empathic relationship with waves currents and tides.

Fig. 1 - Dynamic Equilibrium Yachting Scenario, front and back side

4. Design for NautICS Materials workshop

The scenarios above described setting the frame for Future Yacht concept design opening multiple levels of investigation. The impact of these new materials and hybrid material system on yacht design could unhinge not only the traditional external surface materials of yacht frames and furniture but also the entire design concept and spatial layout.

To verify the potential of ICS Materials in driving a yacht design project, the 3-days workshop *NautICS Materials* was organized and run by the authors engaging students of the Master in Yacht Design of Politecnico di Milano MYD17. The workshop was specifically designed as a first step in approaching ICS Material for a yacht design project. As involved participants with a different background – architects, product designers, and engineers – who had no previous knowledge of ICS material and materials experience, the workshop was conceived as an idea generation training program of a design firm or a shipyard new yacht department.

The workshop objective was twofold: (i) foresee and ideate future scenarios in the yachting sector, by conceptualizing new ICS materials and applying them in Future Yacht design concepts; and (ii) to experiment and test the tentative methodology Design for ICS Materials with its own tools and methods. To achieve its objectives, the workshop had three features. First, the participants were divided into 5 multidisciplinary groups of at least 5 members to reflect a common yacht design studio. Second, the work period was divided into sections to give a rhythm to the design activity, to verify time and tasks and meet efficiency. Finally, a personalized toolkit was given to each team to drive the different design phases. The toolkit, described in the Design for ICS Material methodology, contained Yachting Scenarios Boards specially designed for the workshop, the deck of 48 ICS Materials Cards, and the Concept Canvas.

After a brief introduction, a yacht design trends presentation, and the work-groups definition, the workshop activities were organized in the following four sections conducted in eight hours per day, with a one-hour lunch break. At the end of the workshop, an exhibit presentation of the final work was carried out in order to open a round table discussion on both the design results and the proposed methodology.

Exploration: distribution of the Design for ICS Material Toolkit to get familiar with trends, ICS materials, and Yachting scenarios. The participants were asked to answer the question: «what does the future hold for superyacht design?». The given deck of 48 ICS Materials Cards drove the participants

in comprehend all the elements of ICS Materials to build new concepts with them. The cards were primarily designed to gain an understanding of what ICS Materials are, how they are made, how they work, and how they appear, identifying their inputs and outputs of interaction. Then, participants were asked to start thinking about how the next level of yachting would be like with new smart materials getting inspiration by the Yachting Scenarios Boards. [2 hours].

Definition: a selection of a part of a yacht journey (sailing, mooring/at anchor) to narrow the area of intervention. Then, each group defined the on-board space in which develops the concept project of the new material system according to the experience to enhance. The on-board experience was described through the sensorial, emotional, interpretive, and performative characteristic. As for the first section, the tools proposed to guide the activity were mainly the Yachting Scenario Boards and ICS Materials Cards. [2 hours].

Conceptualization: ideation of new material system through sketches, moodboards, storyboards, and textual notes. The workshop partakers were guided through the novel design methodology by the use of the Concept Canvas. The tool was divided into three sections with the aim of reflecting upon the performances enabled and implied by the concept, based on the individual material components and the composition of them in an articulated system. The first section –material system building – provided an empty schematic graphical representation of a material system recalling the design used in the cards. The purpose was to use the scheme to build a novel material system by getting inspirations from the examples shown in the ICS Materials Cards and combining their constituting elements in a new coherent design. The section ‘material system sketching / picturing’ provided a blank box where students could start materializing the first concept idea with sketching, collages of pictures, or mixed techniques while the last section was dedicated to the material system description. Here participants are asked to outline the concept with textual technical description, performative description, and sensory and experiential description. [6 hours]

Integration: integration of the material system concept ideas into feasible design proposals. Each workshop group developed a Future Yacht concept responding to the proposed Yachting Scenarios and driven by the material experience. The participants were asked to present their project by using conventional design and representation tools and techniques, i.e. drawing and rendering by hand and software. [12 hours].



Fig. 2 - Activities at the 'NautICS Materials' workshop

5. NautICS Materials driven Future Yacht concept

During the NautICS Material workshop activity, the participants conceptualized novel material systems, through the recombination of depicted components, and fully integrated them into design concepts of functional and aesthetic elements of a vessel. As results, they present five Future Yacht design driven by the ICS Material experience. As tangible and material interfaces, they materialize external and imperceptible data enabling a multi-sensory yachting experience, and allowing the user to be more proactive and engaged in their interaction with the spaces and the navigation.

The workshop activity confirmed the potential of ICS Materials to influence the yacht spaces perception through augmented expressions.

In the following sections the workshop projects are listed and described. The projects *Glowrious* and *The Floating Forest* represent the most complete results: the Future Yacht Concepts are driven by the materials technical,

functional, aesthetic and sensorial characteristics. *Heckquilibrium*, *The Underwater Breathing Nest* and, *Dynamic flow* are, on the other hand, focus on interior yacht design only, conceptualising and proposing new ICS Materials for the Nautical and applying them in an onboard interior space.

Glowrious

Based on The warty jellyfish mood, the sailing yacht concept Glowrious, re-images the relationship between the on-board natural and artificial light transforming the yacht hull into a luminescent night illusion system, by embedding photo-luminescent pigments into a smart glass controlled through Arduino. In this project, we could appreciate how the new sensory experience enhanced by the hybrid material system purposely designed influenced the entire vessel concept. A ‘bioluminescent plankton effect’, a diffuse light wrapping the yacht hull, highlight the key on-board areas giving a unique emphasis to the night anchoring and mooring.

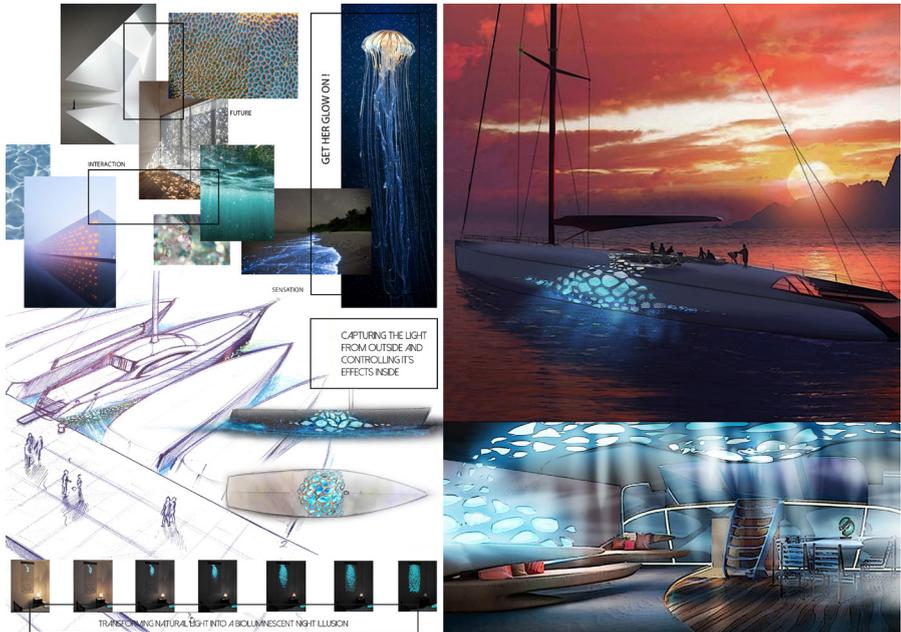


Fig. 3 - Glowrious Future Yacht Concept

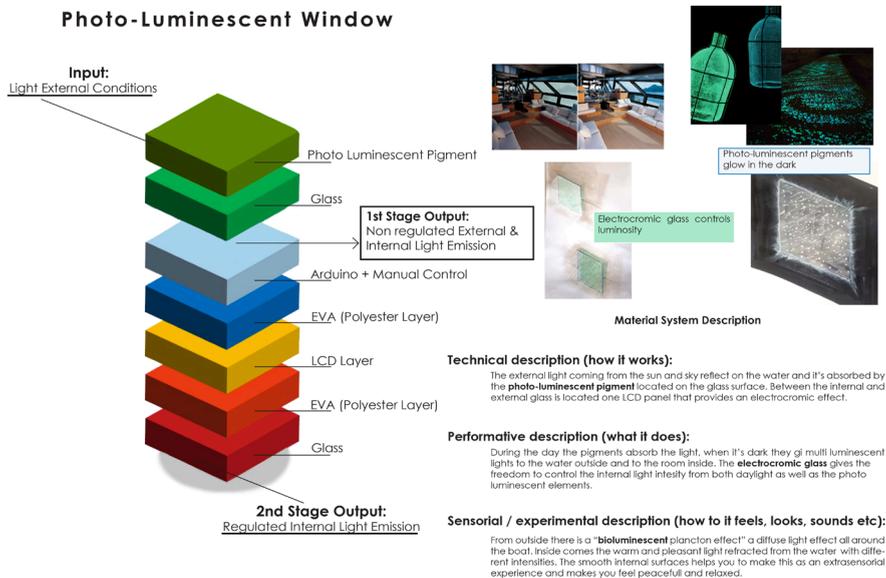


Fig. 4 - Glowrious smart windows material graphical schematic representation on the Concept Canvas

During the day, the warm and pleasant light refracted from the water with different intensities gives an extrasensory experience while sailing transforming the interior saloon in a Nemo Room.

From the technological point of view, the smart windows catch the external light coming from the sun and reflect on the water absorbing by photo-luminescent pigments located on the glass surface. Between the internal and external glass is located one LCD panel that provides an electrochromic effect. The electrochromic glass gives the freedom to control the interior light intensity from both daylights as well as the photo-luminescent elements.

The Floating forest

The Floating Forest yacht design concept overturns the issues of on-board humidity into a design opportunity. Developed from the Moisture poetry yachting scenario, this futuristic floating and sailing biosphere uses inboard moisture to create a futuristic biosphere providing on-board water and light through a twofold hybrid material system. The first ICS Material developed has the primary objective of transforming the excess moisture inside the bio-

sphere to drinkable water and is composed by four layers: a hygrometer sensor, activated absorbent, porous plate, and a hydrophobic slider. The second one is a light emitting material having moisture concentration in living space as input. This material is made out of five different layers, which are also a structural component of the vessel: a hygrometer sensor, an absorber sponge to collect the moisture of the space, a porous aluminium foil as a capillary, a hydrophobic slider and hydrochromic pigment to produce light.

The result is no more a traditional yacht. The 102 meter superyacht is a self-sufficient floating shuttle with a hydroculture forest as her heart.

Heckquilibrium

Inspired by the Dynamic equilibrium yachting scenario this project blends the sailing environment – wind direction and forces, water levels, and waves – in the interior yacht design through materials augmentation.

Sailboats resemble equilibrium, forces of the wind, and the water together. The motion of the wind is simulated on the sails through optic fibres and Bragg Gratings micro-structurally embedded in the core of each sail reinforce fibres. The direction and strength of the wind and the sail pressures are highlighted in real-time in the interior saloon ceiling.

The yacht incline and waves effect are bringing into the interior main quarter through movable plywood panels covered by light-emitting smart textiles and optic fibres responding to pressure sensors. When the vessel is stable, the panels are closed, giving a simple cladding effect. However, when the boat heels the panels open up, offering a dynamic experience by following the angle of the heeling hull. Moreover, dynamic textile patterns added to the plywood panels react to rough sea emitting light according to the wave pressures. From a technical point of view, a nano pressure sensor located along the length of the hull measure heeling angle and water pressure. A control unit that controls both the panel servomotors and the light-emitting optic fibres on each panel independently receives the signal.

The Underwater Breathing Nest

This interior yacht design project, based on the Thermo-taste yachting scenario, reinterprets the yacht interior as a living creature able to react to the human presence and heat creating comfortable areas through shape-shifting smart textiles covering the interior surfaces. Proximity and heating sensor

work together to identify human presence and temperature. Once detected, the information is transferred to the electro-sensitive layers that react expanding itself like a living creature. The interior effect is a boat breathing from the gills enriched by a dynamically controlled comfort temperature.

Dynamic flow

Taking the inspiration from the Wave of good noise scenario, Dynamic flow materializes the wave sound frequencies in an interior waterfall. Thanks to external sound sensors, the wave vibrations are reproduced in a visual effect through a multilayer system. An external microphone for short-range sound waves sends the real-time input to a microcontroller. Then, a cymatic tune generating software, the electrical system and water system provide energy and water at the interior waterfall to create performative-cymatics effect. The waterfall is the cornerstone of the main saloon of the yacht.

6. Reflection on NautICS Material Workshop and its methodology

The two workshops confirmed the effectiveness of the tentative methodology in achieving the intended objectives. The notion of Materials Experience has been learned and applied by the participants, providing inspiration and details to the concepts. Taking inspiration from another industrial sector, the workshop results implement a new generation of material for composite structure, exterior and interior design and sails with dynamic, augmented, and proactive properties. The visionary and speculative approach implied by the theme and the methodology have been appreciated by the workshop partaker that suggest to implement and propose the activity on a larger scale or in collaboration with yacht design firms.

As evidenced by the results of the cases presented is evident enough that the time-wise of a 3-day workshop could be considered too limited for a first approach in designing for ICS Materials. Just two of five groups were able to develop innovative yacht design concepts that could integrate a mix of aesthetic, functional, material, and typological innovation. In most cases, the sensory and experiential properties of the new materials designed affected the yacht interior design only. In these cases the whole yacht concept seemed

disconnected or not influenced by the material that has been conceptualized, resembling conventional yachts, especially on the outside.

With respect to the results obtained, it should be taken in mind that the subjects involved were not only not familiar with the ICS Materials, but also with visioning activities and/or other strategic design tools that could have better enhanced the contribution offered by the proposed tools.

In the light of these considerations, it can in any case be stated that the toolkit proved its potential in guiding designers with no previous knowledge on ICS Materials and materials experience from material understanding, to the conceptualization of novel material systems with different degrees of complexity combining inactive materials and smart material components. The integration of the materials into feasible concepts drives the design process in defining new Future Yacht with focus on material experience. The use of the deck of cards partially overcame the limitations caused by the lack of physical samples of the actual materials and provided immediate and effective information in them. However, future development of the methodology may integrate material samples and rapid novel material prototyping with the use of advanced and/or additive technologies and open-source hardware and software. The possibility of applying single-board microcontrollers and microcontroller kits to augment inactive materials could both enrich the workshop conceptualize phase and give direct feedback on the performative, sensory, and experiential proprieties of novel materials conceptualized.

To foster and exploit the potential of ICS Materials, future application of the methodology in a design workshop could direct such materials to create awareness, alleviate, or contribute in solving today's environmental problems. As introduced by The Floating Forest concept, ICS Materials may visualize environmental information to create awareness on the quality of air, help in the filtration and depuration of polluted water while sailing, or be used as an alternative and sustainable source of energy-harvesting for self-sufficient boats. Furthermore, new ICS materials from natural sources or with a low impact in production, second-row materials, or DIY materials (Ayala Garcia & Rognoli, 2017) could be the focus of future research and workshops.

In order to strengthen the workshop model and its methodology, larger experimentation – not only in education but also in practice with industrial partners – and should be taking into consideration. Furthermore, the outcomes and inferences from this first pilot application in the Yacht Design sector

suggest applying the Design for ICS Materials methodology to other fields. Most prominent areas seem to include – but not limited to – wearable healthcare objects, transportation, and automotive design, mobile space suite, smart, micro and/or temporary architecture, consumer electronics, and smart and conversational furniture.

Acknowledgments

The NautICS Material workshop was carried out during XVII edition of the MYD Master in Yacht Design at Polidesign, Politecnico di Milano. We thank the colleagues Stefano Parisi and Valentina Rognoli, taking part to the workshop conceptualization and execution stages.

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6. Design for ICS Materials. The development of tools and a method for the inspiration and ideation phase

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1. The need of a systematic method to design for ICS Materials

As presented in the previous chapters of this book, Interactive Connected Smart (ICS) Materials are an emerging area of materials and technologies that are experimentally – or can be potentially – introduced in some fields of application, from responsive architecture to smart objects. In some sectors such as textiles, examples of ICS Materials not only are more likely to be seamlessly integrated due to satisfactory technical requirements – e.g., the degree of required miniaturization and flexibility of technologies – and the technological and manufacturing apparatus that allows seamless integration. Some practitioners already started to develop their own procedures to explore and design with and for materials with interactive, smart and connective characteristics. However, to enable them to design with and for ICS Materials and introduce them in their design practice, a systematic methodology with methods and tools made on purpose are required.

This methodology can also be used as a way to inform designers and to transfer knowledge to them. This is particularly relevant if we consider the field of education, where some experimental activities have been carried out using specific approaches, methods, and tools. By allowing both practitioners and students to explore, learn, ideate and develop about these materials, not only we transfer knowledge, but we build and reinforce skills and capabilities. These will contribute to the establishment of new kinds of professional profiles able to manage such materials and to advise companies for their integration.

In the chapter, we depict the State of the Art, with a broad survey on Material Design methods and tools involving interactive, connected, and smart materials. We mainly focus on design education, a field where more experi-

mental approaches are applied and then exposed through publications. Then, we introduce the ‘Design for ICS Materials’ method and its supporting tools developed in the scope of the project ‘ICS Materials’.

2. Approaches, tools, and methods (for learning how) to design interactive, connected, and smart materials: State of the Art

Before setting up a new method for designing for ICS Materials, we drafted the State of the Art, focusing on approaches, methods, and tools applied in design processes and learning environments. Indeed, in design education, some teaching activities have already been experimentally carried out to explore and apply these materials in different sectors. Although these experiences are still relatively recent and experimental, it is possible to recognize precise design and teaching methods, approaches, and tools that have been applied to transfer knowledge, experiment, ideate and develop a design with interactive, connected, and smart materials. Among these methodologies, some of them are focusing specifically on materials with interactive, connective, and smart characteristics (e.g., smart materials, smart material composites, tangible interactive surfaces, e-textiles), while others address generically to emerging material, including ICS Materials, but not limited to. We present a selection of design process and teaching experiences identified from the literature review and based on our experience as educators, pointing out at the most relevant observations on the approaches, methods and tools that have been applied. For a broader review of design teaching methods, we invite you to read (Parisi, 2020).

Mixed sources for learning and understanding ICS Materials. One of the most applied approach to gain knowledge about materials is the *mixed approach* (Haug, 2018), combining multiple learning sources. Examples of these sources are direct experimentation with materials, reading texts, watching videos, and discussions with peers, instructors, and experts. Tangible materials samples are efficient tools to gain understanding about novel materials and stimulate the creative process through direct manipulation (Haug, 2018; Rognoli, 2010; Pedgley, 2010; Ayala Garcia, Quijiano and Ruge, 2011). In this respect, one of the problematic issues when dealing with advanced materials – including ICS Materials – is that physical samples might be not easily accessible. Therefore, it is fundamental to provide designers and students with the opportunity to understand ICS Materials in the absence of physical

samples. Examples in education show tutors replacing samples with other alternative learning materials in the format of databases (Hölter et al., 2019) and in the format of canvases or cards (Colombo, 2014). Considering the novelty of ICS Materials, other principal sources for gaining and sharing information and inspirations are open-access platforms presenting case studies, instructions, and tutorials, like *Materiability* (<http://materiability.com>) by Manuel Kretzer and Openmaterials (<http://openmaterials.org>) by Catarina Mota.

Kretzer (2017) argues that it is a priority that designers acquire active material literacy before applying them, including learning how to use and qualify their potential. The suggested learning approach is through multi-disciplinarity, hands-on explorations, digital fabrication, access to open-source information and technologies, and development of speculative and critical applications. Similar approaches are shared within the *FabricAdemy* program (<https://textile-academy.org>), coordinated by Anastasia Pistofidou (FabTextiles / Iaac FabLab BCN) and Cecilia Raspanti (TextileLab Amsterdam / Waag Technology & Society).

The role of application and contextualization. The methods presented in these pages are fundamentally embedding *Active learning* (Bonwell and Eison, 1991). In material education for design, students are often engaged within a design challenge or a project brief, as it conventionally happens in practice.

This denotes a tendency towards *application-oriented* design processes in education and training programmes for designers. These methods are based on the application of the materials into a product, to challenge their limits and potentials, and promote new product development and innovation. Often, they involve stakeholder, for examples companies, to contextualize the materials and reinforce the connection between Academia and Industry (Piselli et al., 2018). Another common approach is *context-driven*. The context – whether it is an industrial sector, a situation, or a broader social scenario – is defined as a starting point of the design process and provides borders to the limitless possibilities of ICS Materials. In a context, ICS Materials and their resulting application will be situated in a discourse with industry and society involving not only technological limitations and opportunities but also social necessities. Indeed, one challenge related to ICS Materials arises from a significant risk of developing a product embedding an emerging material or technology, without creating a real value for society.

On these lines, the Design-driven Material Innovation Methodology (Dd-MIM) (Lecce and Ferrara, 2016) is a systematic approach for design students and practitioners, research centres, and small-medium enterprises, based on the understanding of the broader socio-cultural scenario before selecting advanced materials, including smart ones. It allows the development of one

or more materials starting from scientific discoveries, material patents, or production processes, to identify scenarios of application and to develop new products. DdMIM has been used in the application of smart materials and interactive technologies for tangible interfaces in products and interiors in design workshops at the School of Design of the Politecnico di Milano (Ferrara and Russo, 2019).

Speculative and critical design approach. Some other methods are based on a *speculative design approach* using critical thinking and prototyping to question technological, societal, and ethical implications of advanced materials and technologies in future scenarios. By envisioning and projecting future development and application of ICS Materials, this approach overcomes their evident current technological limitations and scarce availability. In this respect, Barati et al. (2015) argue that “designer’s naïve perspective with respect to every technical detail of a technology allows them to see new applications.” One example of speculative design method in the context of smart materials is the *Dystopian Thinking*. It uses science fiction-based scenarios as a starting point to generate ideas of smart materials wearable applications in future or alternative situations¹. The design process was supported by a toolkit based on inspirational cards and canvases.

With a more hands-on approach, the InDATA project team at the Design Department of the Politecnico di Milano (<http://www.indata.polimi.it>) carried out an experimental design activity in the format of the Hackathon “Data < > Materials”. The design process was focused on developing interactive devices and wearables by combining speculative design, do-it-yourself bioplastic making, electronics programming and embedding, and digital fabrication with the support of the Fab Lab environment (Parisi et al., 2021). The design process used future scenarios involving the use of technologies as a starting point and was facilitated with mixed learning and design tools with the aim of understanding materials and technologies and carry out material experimentation, concept ideation, and prototyping.

On these lines, another design approach is the one applied by young designers and students at the Institute for Material Design IMD at the Offenbach University of Arts and Design (<http://imd-materialdesign.com>). There, they are dealing with active material systems, augmented with digital, adaptive or interactive components. The design process is based on hands-on exploration and prototyping of materials demonstrators, working in a hybrid design

¹ El Futuro de los Wearables Dinamicos / the Future of Dynamic Wearables” (<http://blog.materfad.com/2018/02/materfad-organiza-un-workshop-sobre-wearables-en-la-mobile-week-barcelona-2018>; <https://www.piscolabisdesigners.org/workshop-future-of-wearables-from-dystopian-thinking-x-jessica-fernandez-cano>).

space where form, material, and technology overlap. The results of this hybrid practice are prototypes encouraging the discussion about material authenticity and speculative applications (Parisi, Holzbach and Rognoli, 2020).

In the workshops *Coded Bodies* (<https://codedbodies.com/>), interaction designer Giulia Tomasello engage companies, design practitioners and students in a design process combining traditional textile techniques, sensing and actuating technologies, smart materials and biological textiles to develop a speculative concept and prototype physical soft wearables, adaptive structures, and active second skins.

Multi-disciplinary approaches. The urgency for creating a multi-disciplinary environment to learn, experiment and develop applications of ICS Materials is expressed in a large number of cases. Indeed, ICS Materials area is mainly situated in the intersection between design, materials, and interaction, practically involving electronic circuits design and material crafting, along with design capabilities. Since only a few cases report to actually operate in this multi-disciplinary field with co-tutoring or cross-field collaborations (Schmid, Rümelin and Richter, 2013), this is a still major gap. The project *Datemats* proposes a training methodological framework for companies, design practitioners and students to design with and for four areas of emerging materials and technologies, including ICS Materials. This framework is characterized by cross-disciplinarity for understanding, shaping, and applying these materials (Ferraro and Parisi, 2020).

Cross-disciplinary knowledge includes sustainability. The design process used at the *Interactive Organisms Lab* coordinated by Katia Vega focuses on exploring sustainable interactive objects and wearables starting from hands-on exploration with organic and growing materials (mycelium) in combination with interactive technologies (Vasquez, Lazaro and Vega, 2019).

Experiential learning through material-centred approach. An approach that is fundamentally embedded in design practice and education is *Experiential learning* (Kolb, 1984). This approach allows designers to gain procedural knowledge about novel materials by learning through making (Pedgley, 2010). Most of the mentioned methods emphasize direct experimentation through exercises and hands-on exploration. *Material tinkering* is a goal free and playful exploration with physical components – both materials and technologies – for understanding their potentials and guiding further developments (Rognoli and Parisi, 2021; Parisi, Rognoli and Sonneveld, 2017; Santulli and Rognoli, 2020; Alarcón et al., 2020; Asbjørn Sørensen, 2018). Schön and Bennet (1996) described how the design process could be approached as a conversation with materials, through which the practitioner gets to know the materials.

On these lines, the *Enactive Environments Lab* (<http://www.enactiveenvironments.com/>) founded by Karmen Franinović reflects on the direct exploration of responsive and active materials (Franinović and Frankze, 2019) in creative research processes as a negotiation with materials – with their form, behaviours, and interaction as one – rather than imposing ideas and forms on them. Creative hands-on exploration using analog and digital materials, tools, and methods, as well as the experience of the user enhance embodied and situated knowledge engaged in both tacit and creative process and physical interaction.

Therefore, it becomes necessary to create methods based on the central role of materials in the design process. Often one material or a selection of materials are the starting point of the design process. This is the case for the *Material Driven Design (MDD) method* developed by Karana, Barati, Rognoli and Zeeuw van der Lann (2015). Practicing this method, practitioners and students start from a material at hand and design for materials experience (Karana, Pedgley and Rognoli, 2014), by tuning their physical qualities, sensory profile, emotional and meanings associations. This method targets novel materials with yet limited applications and unrecognizable identities – including ICS Materials – to foster meaningful materials experiences and ultimately materials acceptance by the society and the market. The method was applied on designing with and for intelligent composite materials, specifically an underdeveloped piezoelectric and light-emitting smart composite material (Barati, Giaccardi and Karana, 2018; Barati, Karana and Foole, 2017; Barati, Karana and Hekkert, 2015; Barati et al., 2015).

Simulation techniques replacing physical samples and inspiring forms and interactions. One of the problematic issues of designing and teaching for ICS Materials is often the scarce access not only to materials samples, but also to equipment, facilities, and multi-disciplinary environments to experiment and produce prototypes. Instead, simulation can be used to exemplify or mimic the sensory qualities or the physical behaviours of the intended material by creating, collecting, and combining other material samples (Karana et al., 2015). Metaphors and analogies can be used to inspire and communicate the performance and behaviours of smart and interactive materials. Experience prototyping and bodystorming techniques can be used to physically explore, test, and define the functionality and performances of ICS materials in the early stages of the design process or in the absence of physical materials or equipment (Piselli et al., 2015).

Even in hands-on experiences, metaphors can be used to inspire forms and behaviours in the ideation phase. This is the case of the design process

applied by Schmid, Rümelin, and Richter (2013) focused on the development of glass-based tangible user interface, starting from the suggestions provided by the glass forms and qualities which are then implemented with electronics.

User-centred approaches. The user interaction and expectations in relation to the material aesthetics and performances are essential, both considering physical body involvement and emotional engagement. In the design process described by Russo and Ferrara (2017), the role of the whole-body experience and somaesthetics was vital in ideating with interactive materials. In another case (Colombo, 2014), the role of user experience in dealing with smart-material based interactive products is emphasized in the use of tools for enhancing product sensory experience. Like the afore-described MDD method, these processes are fundamentally user-centred, considering the user involved since the initial stages, often through user studies.

3. The ‘Design for ICS Materials’ method

Starting from this survey on methods, tools, and approaches, we defined a tentative method to design for ICS Materials. The method is addressed to design students and practitioners, or to mixed-students classes and multi-disciplinary teams, including design expertise. The objectives of the method are listed as follow.

- To understand ICS Materials components, architecture, and capabilities, using inspirational best examples and encouraging a mixed-method learning approach
- To engage students and practitioners in an active and experiential learning process with a design challenge or project brief
- To encourage multi-disciplinary collaborations within a mixed group
- To provide a scenario, context, or situation as a starting point to drive the exploration of opportunities and, then, the ideation of a solution (case-specific and context-driven approaches)
- To envision future scenarios for ICS Materials using a speculative approach
- To support the ideation of design solutions integrating ICS Materials with an application-oriented approach
- To explore and identify the experiential qualities of the solution when interacting with the user, encouraging a user-centred approach.
- The method has a flexible structure that can be integrated into design

activities, courses, and short workshops focused on different application sectors and design challenges. The main phases of the method are 1) Exploration, 2) Definition, 3) Conceptualization, and 4) Integration. A demonstration and description of the stages is contained in the previous chapter (Chapter 3.5). For the pilot application of the methodology, no hands-on activities involving materials and making techniques were provided. The main reasons are the scarce availability of needed materials and technologies, as well as the limited timeframe imagined for the initial application of the method. Therefore, instead of a hands-on approach, we opted for replacing physical materials with a toolkit of descriptive materials using textual and visual information, and we encourage a simulation approach, using analytic tools such as maps, schemes, descriptions, and creative tools visualization, mood-board, collages, and sketches.

4. The ‘Design for ICS Materials’ toolkit

As for the method, the supporting toolkit is a flexible and modular set of tools that can be adapted to different applications that can vary according to the timeframe, participants, structure, and application field. For the description of the toolkit, we may use examples of contents from the first application of the methodology in the workshop NautICS Materials (Parisi et al., 2019a; 2019 b), described in this book (Chapter 3.5). The tentative version of the toolkit to support the methodology is composed of three elements, as follows.

Reference scenarios. Scenarios are the starting point of the design process. They represent a context, a situation, an issue (for instance an environmental or social problem), or a field of application. The context can be more or less broad, more concrete or abstract, established/present or future/speculative. They vary according to the topic and aim of the activity. They can be provided through visual and textual contents, for example, with boards of images and mood boards supported with a title, description, and references. One example of scenarios boards is presented in the previous chapter, basing on potential Yachting scenarios. In that case, each scenario was presented through an inspirational A4 board providing a mood board, textual storytelling, and different keywords. This tool is used mainly in the Exploration phase.

ICS Material Cards. A deck of 48 cards was designed with the purpose to help students and designers understand all the elements of ICS Materials and build new concepts with them. With the cards, by gain an understanding of what ICS Materials are, how they are made, how they work, and how they appear, and identify their inputs and outputs of interaction. Each card shows an example of ICS Material, with pictures and textual information, i.e., name of the project, name of the author, a short text describing how it functions and performs, and a graphical schematic representation showing its components divided into layers, inputs, and outputs (Fig. 1 and Fig. 2). To do that each example was deconstructed into its constituting elements. The examples that have been selected by the authors to build the cards deck encompassed materials, surfaces, and material-based objects and systems used in many applications, with different behaviours, complexity, and technological readiness levels. This tool can be used in the Exploration stage, for learning and informing activities by reading the content of the cards. Also, it can be used in the Definition phase, by clustering them and selecting the most relevant and promising examples according to the scenario.

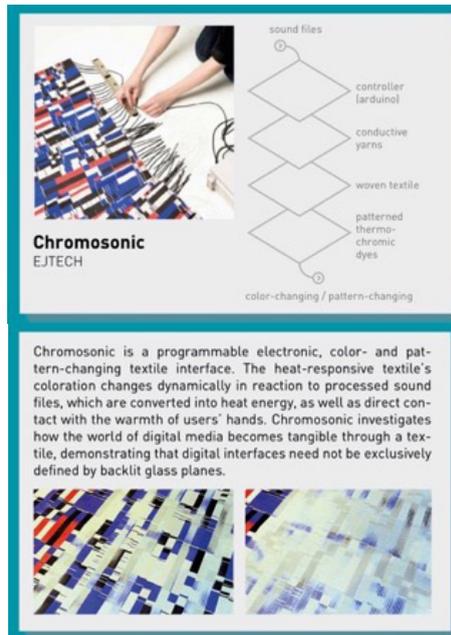


Fig. 1 - ICS Material Card of the case Chromosonic by EJtech (front and retro)

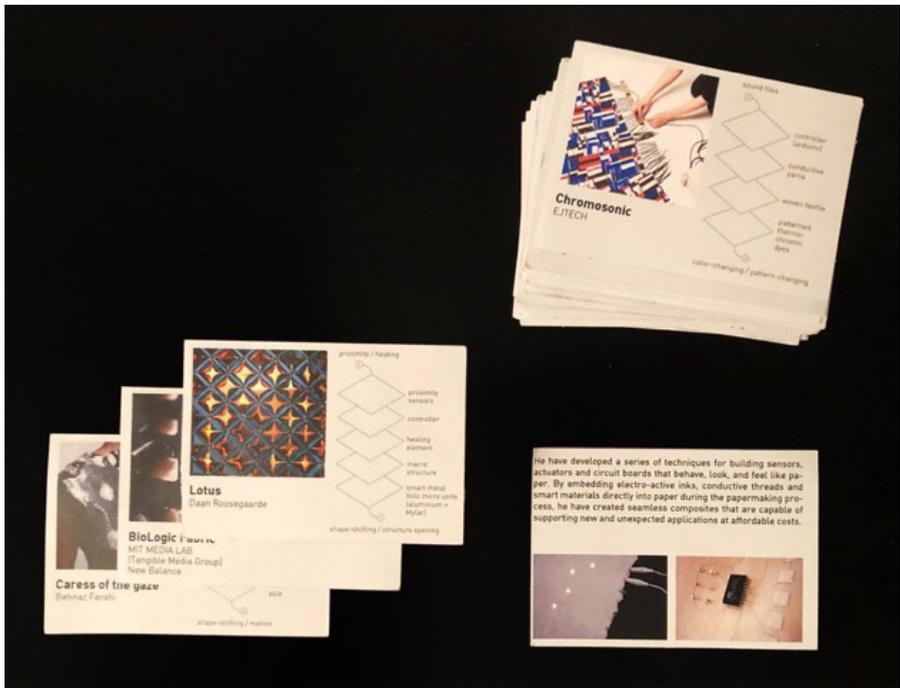


Fig. 2 - A selection of ICS Materials Cards

Concept Canvas. A Concept Canvas in A3 size was designed to be used mainly in the Conceptualization and Integration phases (Fig. 3). The purpose of the canvas is to guide students and designers through the novel design method to conceptualize a new ICS Material. The canvas was divided into three sections, namely (i) material system building, (ii) material system sketching, and (iii) material system description. The first section provides an empty schematic graphical representation of a material system divided into layers with blank spaces to complete with the names of components, input, and output. This recalls the same design used in the cards. The purpose is to use the scheme to build a novel material system by getting inspirations from the examples shown in the ICS Materials Cards and combining their constituting elements in a new coherent design. Although the scheme represents a simplified laminate construction, other ways of integrating and combining elements in a composite structure may be considered. The second section provided a blank box where students and designers can start materializing the first concept idea with sketching, collages of pictures, or mixed techniques. The third section asks to outline the concept with textual technical description ('how it works'), performative description ('what it does'), sen-

sory and experiential description (‘how it feels, looks, and sounds; which emotions, meaning associations, and actions are elicited’), basing on the layers of Materials Experience framework (Giaccardi and Karana, 2015). This last section aims to reflect upon the performances and experiences enabled and implied by the concept, based on the individual material components and the composition of them in an articulated system. Even if we suggest to follow the steps sequentially, the three activities can be carried out in parallel with an iterative approach, as each section informs the others.

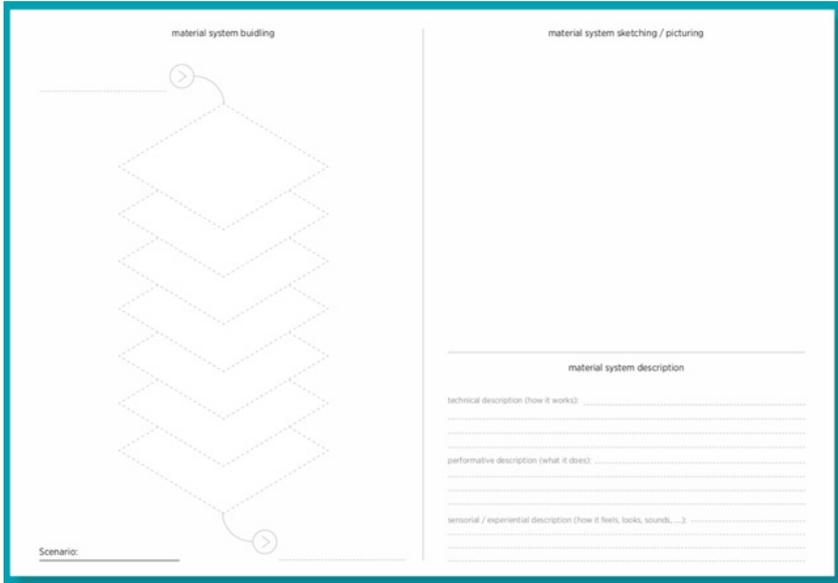


Fig. 3 - ICS Material Concept Canvas

5. Conclusion and final remarks on the method

In this chapter, we presented the need for a systematic method for designing for ICS Materials and for teaching how to design for ICS Materials. State of the Art on methods, tools, and approaches is presented by literature review, with the main focus on education in design. The method, its objectives, phases, and supporting tools are described. In the previous chapter (3.5), a pilot application of the methodology in the design education context is described: the workshop “NautICS Materials” (Parisi et al., 2019a; 2019b). The workshop used the context of the nautical sector and related environmental inputs and triggers – for example, moisture, light, movement and

sound – as the starting point for a multidisciplinary design workshop on ICS Materials using the here proposed method and supporting toolkit to design in the absence of physical materials. The workshop approached the topic with a speculative perspective, acknowledging that such materials are quite advanced for the current yacht sector, but could be potentially applied in concepts of future yachts. Besides this pilot experience, the method and tools can be transferred to other sectors or to scale up in larger experimental and applied actions – not only in education, but also in practice with industrial partners – for the integration of smart materials and technologies in the design space.

The method may prove its potential in guiding the design phases from the material understanding, to the new materials conceptualization, and their integration into design concepts. Among the elements of the toolkit, the cards may overcome the limitations caused by the lack of physical samples of the actual materials and provide immediate and effective information on the materials. However, future development of the methodology may integrate material samples and prototyping.

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This present book covers a series of outstanding reputation researchers' contributions on the topic of ICS Materials: a new class of emerging materials with properties and qualities concerning interactivity, connectivity and intelligence. In the general framework of **ICS Materials**' domain, each chapter deals with a specific aspect following the characteristic perspective of each researcher. As result, methods, tools, guidelines emerged that are relevant and applicable to several contexts such as product, interaction design, materials science and many more.