DIGITALLY ENHANCED DESIGN

Breakthrough tools, processes, and expressive potentials

edited by Maurizio Rossi and Davide Spallazzo

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Foreword

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The relationship between design and the digital world has progressed in two directions since the dawn of developing the first computer systems. The first phase of this relation saw the digital world become the object of design, in terms of forms, algorithms, and interaction methods. With the advent of CAD systems, the digital world has proposed itself as a design support tool at various levels of scale, from the design of industrial products to interiors up to the scale of large infrastructures. Today we are witnessing the full development of the biunivocity of the relationship between design and the digital world. The latter simultaneously supports design and is the subject of designing the behavior for morphological and systemic elements of modern products and buildings.

In the context of the processes concerning digitally enhanced design, we should mention the new frontier of computational design, which consists of applying computational strategies to the design process. These issues have also been brought into building automation and smart home in architecture, where interaction design has developed based on the IoT. The behavior of the new building's complex systems, and even its morphology, may depend on the collection and management of data deriving from the behavior of people and the changing environmental conditions inside and outside the building. In the context of architecture, one of the classic examples is the control of natural light to enhance it but keep it within acceptable parameters for the needs and lifestyles of the interiors. Thanks to the IoT, artificial lighting, HVAC, and audiovisuals are now connected to new building automation. The new frontier is no longer just automation but a new level of intelligent interaction, AI-infused systems able to learn over time and modify their behavior accordingly.

Today sensors, increasingly pervasive and connected, can provide different information. This info regarding the occupants and the indoor and outdoor are sent to robotic management systems capable of learning from human behavior and natural environment variations. The purpose is to set up integrated systems of the building for people's well-being and energy saving. Sensors have come to the point of using computer vision for the analysis of environments and user behaviors. However, in democratic countries, these systems find little acceptance by users, especially in the workplace, when they allow workers to be identified and monitored. Next to the video sensors, thermopile array systems are being developed that would enable the analysis of the environment and the activities that take place there in the infrared field, thus ensuring privacy. If solutions to protect personal data while ensuring full operational capability are emerging, scenarios of domestic environment integrating AI solutions may emerge and be discussed on the one side as utopia/dystopia for end-users and as opportunities for designers on the other.

This kind of innovation leads the design and management of spaces to become a time-based process. This raises important questions regarding the representation and formalization of the project for its realization, management, and future maintenance of complex, integrated, interactive systems that should be able to learn. The formalization of projects with this degree of descriptive complexity, no longer only formal but also managerial, can be tackled today only thanks to Building Information Modeling methods.

While BIM represents the future in the design methodology of buildings, the digital world tools available today cannot provide all the solutions necessary to manage interior design. This area lacks fundamental tools to manage color and lighting design in a reliable way between the digital and real worlds. All the digital world tools should be integrated, reliable, and supportive in the design process. Through calculations and photorealistic representation, they should allow virtual prototyping of spaces. Only in the final phase can provide helpful tools for the presentation and multimedia communication of the project that must not be confused with those of the beautiful images typical of communication design.

There is an open problem concerning the importation into the digital world of the colors and lighting of reality. On the other hand, there is also a problem concerning the correctness of colors and lighting design in the digital world when forecasting the real world. These problems arise from the fact that in the physical world, as in the represented digital world, there is the human being with visual perception, which is a cognitive process that has not yet been described in all its aspects. Do not deceive the presence of sciences such as photometry and colorimetry because these historically underestimate the importance of real visual perception, well known in the design practice since the Bauhaus times. Our optical system does not work as a precise measurement tool or a camera with the image that reaches our eyes; instead, it is based on a process of spatial perception not yet fully described. Each visual element depends on the context. This is even more evident in the digitization of cultural assets, for their cataloging, safeguarding, and enhancement, which are central to design for cultural assets. For historiographic reconstruction and enhancement of the work of art, the level of acquisition in the digital world has arrived at the analysis of the spectral and non-visible radiation, which has allowed the reading of the understated drawings in paintings and the studying of unreadable scripts.

On a lower scale, in the modern design process, in the manufacturing sector through CAM and digital numerical control robots, new smart materials are now available, but an environmental sustainability problem remains open. The integration achieved between conventional design materials and new technologies of the digital world has led to the definition of a new class of materials, which we can define as phygital, with dynamic behaviors thanks to their ability to straddle the physical and the digital world. It is also thanks to a recovery of the aesthetic value of the project, accompanied by an experimental reinterpretation of basic design, that these materials, changing in shape and appearance, now give new degrees of freedom to the design of industrial products.

Alongside aesthetics, however, there is an important open issue of design ethics in the furniture sector. We know the values of the circular economy cycle, as reinforced by the European Green Deal launched in 2019. An enormous accumulation of non-recyclable waste characterizes the unbridled consumerism of today's capitalist system. Unfortunately, European data show that only 10% of furniture products are recycled in the supply sector while 90% ends up in landfills. In this context, the digital tools of Industry 4.0, such as the management of data flow from the 3D project to the product, smart robots, 3D printing, autonomous handling systems, and intelligent energy management, can facilitate the transition towards a factory based on principles of renewable and clean energy to ensure eco-friendly production.

This book recalls theories and experiments in the relationship between the physical and digital world with a multidisciplinary approach and different methodologies typical of design research and practice, placing itself in an open research path with further developments in the coming years.

1. New scenarios for lighting design tools

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Abstract

The lighting project comprises several steps, each of which involves using tools (and skills) that can vary in the process phases. A designer should know the fundamentals of lighting to design in full awareness, but numerous software tools can provide valuable help beyond this. The negative aspect of this variety is that heterogeneous outputs can be obtained due to individual designers' skills and preferences. Although diversity is a value to be pursued, it is also true that the results must still be correct. For example, the most common three-dimensional modeling software are not explicitly designed to take care of the lighting project. By contrast, software specializing in lighting design often provides results that, although correct from the point of view of the calculations, are inadequate in reproducing reality. An alternative is to adopt a Building Information Modeling (BIM) type of software, manage complexity, and integrate them with other programs that can somehow interface. This solution allows managing the project to comply adequately with the directives that promote BIM as a mandatory methodology for future projects. This hybrid approach, albeit imperfect, is functional, hoping that specialist software developers and product companies (for their catalogues) will quickly adapt to the BIM system. While waiting for a perfectly integrated methodology, some fundamental problems for lighting design must be addressed.

The reproduction of the products and their associated characteristics (outside the context of specialized software) is not easy to achieve. The correct simulation of the finishes, which involves implementing standard procedures to acquire the project's colors digitally, is another

topic that needs further discussion. This chapter describes original solutions at the Light Lab of Politecnico di Milano to search for the best method to achieve photorealistic and photometrically correct results.

1.1 Introduction

Lighting design is a professional field that requires a well-defined set of expertise. Most lighting designers are trained as architects, but it is not uncommon to find professionals from electrical or electronic engineering studies or design-oriented faculties. However, the absence of a chamber of lighting designers (mostly belonging to various associations) results in a significant heterogeneity in the approach to the project. Numerous differences can be found in lighting projects. First, the application field already determines distinctions in the deliverables that are produced. For example, a project for works in the public administration area requires more detailed documentation than the private one. Other differences may arise from the design context; the lighting of an interstate road requires calculations, simulations, and documents that differ from those for cultural heritage, retail, hospitals.

In addition to these differences, the competencies of the lighting designer also affect the approach to the project; some designers are more interested in the expression of the concept underlying the project, while others focus on energy efficiency or in solving specific technical problems. Finally, and this happens above all in the private sector, the most disparate requests of the client translate into the variability of approaches, which are potentially different for each project.

Although diversity and novelty in the solution of design challenges are considered values, it should also be assumed that it is necessary to realize a project at the end of this flow of ideas. Projects must be feasible; they must define a series of lighting values, power needs, electrical consumption, number of specific lighting fixtures, positioning, aiming, etc. To facilitate designers to follow a single direction in the project, in 2016, the Italian Standardization Body produced a standard (UNI, 2016) whose purpose is to unify the lighting design process and the related documentation. This standard, which has no equal in Europe, provides definitions, procedures and the material that must be delivered to the client. However, the norm does not go into the details of specific tools to be used. As regards the graphical drawings, it remains very open to the type of data representation. Terms such as *“photo simulations”* or *“graphic rendering in an appropriate scale”* are used, but without going into details on the method of production of these elements. Consequently, each designer is free to adopt the techniques he deems appropriate to simulate the project’s appearance, from the production of photo simulations with raster imaging software to the use of 3D applications for the production of photorealistic renderings. In the standard, emphasis is instead placed on the possibility of using lighting calculation software as long as they are *validated*. There are numerous software (or, more precisely, calculation algorithms) that allow one to simulate the interaction with matter to produce photorealistic images. Still, the type of programs mentioned in UNI 11630 does not refer to the ability to create such images, as much as instead to the possibility of serving as a support for the lighting calculation.

1.2 The calculation of lighting

Since the appearance of three-dimensional modeling software, research has been concerned with simulating the lighting on objects correctly. At first, virtual sources were used, known as OpenGL (Point light, Spot light, Ambient light, Directional light). These virtual lights were designed best to mimic the types of sources present in nature, so the spotlight simulated the cones of light, directional light served as sunlight, ambient light emulated indirect light, etc.

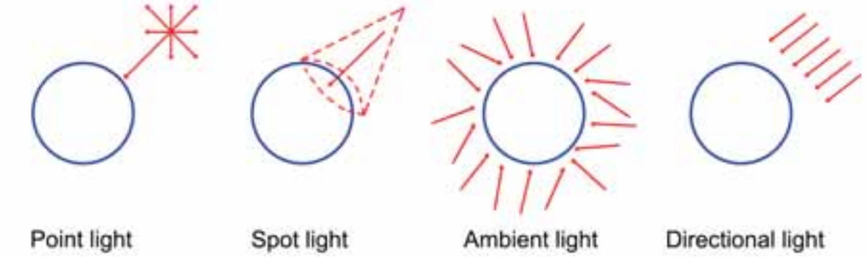

Fig. 1.1 - From left to right, different generic light sources commonly used in 3D software: Point, Spot, Ambient and Directional.

The render engines worked with local computation models (flat shading, Gouraud shading, etc.) and ray-tracing (Goldstein and Nagel, 1971). With these methods, it was possible to represent glossy and reflective surfaces, transparencies and sharp shadows. Still, it was impossible to calculate the diffused light, which was mimicked by the ambient light (assigning a specific value to a "fill light"). Nevertheless, it was possible to obtain digital images that were quite plausible with this method even though they were far from what reality would have been by reconstructing the space with actual lighting products.

As time passed, the quality of the simulations improved. Software packages began to introduce the radiosity algorithm (Goral *et al.*, 1984), which allowed the simulation of the interaction of light with diffusive surfaces. By combining radiosity and ray-tracing, the first software oriented to lighting analysis began to appear (such as Lightscape, in 1994). These applications were capable of providing not only increasingly photorealistic renderings but also improving photometric accuracy. Further improvements have come with more recent engines (Ng *et al.*, 2001), such as photon mapping (Jensen, 2001) or the physically-based approach (Pharr, Jakob and Humphreys, 2017; Chen, Cui and Hao, 2019). The incredible complexity of the light-matter interaction makes it necessary to apply simplifications in the calculation, which otherwise would result in timing not compatible with the reality of professional practice. Despite this, however, the calculation engines available today make it possible to obtain a satisfactory lighting simulation to support the lighting project. This result is also possible because instead of OpenGL lights, photometric files obtained from the measurement of existing luminaires are used.

1.3 Representation software vs Lighting design software

Even if the render engines used are the same, it is possible to distinguish between the software used only to produce photorealistic images and those used to support the lighting design. This distinction depends on various factors, but the main reason remains the intended use of the software. The production of a "photorealistic" image of an environment (for example, the simulation of an architectural project) aims to promote the solutions designed to the client. A beautiful image helps the designer to sell better his project, and in this context, the *lighting analysis tools* are not essential. Sometimes it is also possible to "cheat" by tweaking some parameters to make the image even more attractive (more saturated colors, lens flares, halos, materials more reflective than they should). The use of lighting design software sees its strength in the presence of lighting analysis tools. For example, these software packages can give feedback on the lighting levels on specific surfaces or evaluate the uniformity of illuminance on a visual task, rather than the *modeling factor* on the occupants' faces, etc. Rendering is a secondary feature, and in any case, it is always subordinate to the photometric values obtained. There are no "embellishments", as they would then be refuted after constructing the actual space.

Fig. 1.2 - A render generated with 3D modeling software. The purpose of the image is to promote the solution designed by the architect. Therefore, the image is realistic, but some errors are visible; the interior/exterior balance of luminances and the sources reflections on the windows (too visible for a daylight scene).

Fig. 1.3 - Render of a lighting software. The image is photometrically accurate, but the poor management of the 3D geometry causes a loss in photorealism

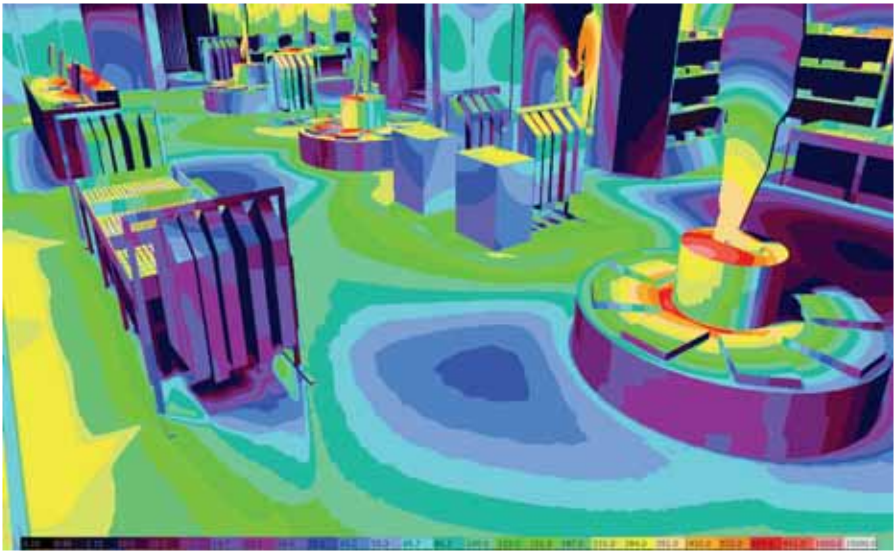

Fig. 1.4 - Non-photorealistic render generated by lighting software. This type of image (coupled with a proper color scale) acts as a tool to check the correct illuminance values in the space. This allows an accurate idea of the amount of light on the surfaces regardless of image exposure levels.

Fig. 1.5 - Rendering obtained using a photo-editing program. Starting from daytime images, one can recreate a night scene by adding layers of black. The images thus obtained, however, usually lack photometric accuracy.

Calculation grids, verification points, non-photorealistic rendering, automatic production of verification reports are the primary tools of this kind of software.

In order to be considered reliable, a lighting calculation software must be "validated", that is, it must comply with the criteria set out in the *technical document 171:2006*, produced by the technical committee 3.33 of the Commission Internationale de l'Éclairage (CIE, 2006). However, this step is not required for 3D representation software.

The most popular lighting design software are Agi32 (Lighting Analysts, 2021), Dialux (DIAL GmbH, 2021), Relux (Relux Informatik AG, 2021), Litestar (Oxytech, 2021).

Generally, lighting calculation software is not particularly complex in terms of modeling, texturing and material management tools. This makes the time required to master them considerably less than that of representation software but causes apparent limitations in the generation of photorealistic images. Moreover, even if the calculation algorithms are comparable (though often simplified), the vertical software (lighting design) are not efficient in the management of complex geometries.

The direct consequence of the lack of photorealism in verification software is that when designers want to obtain high-quality images (for large commissions or big tenders, for example), they find themselves having to resort to other tools. These might be the 3D modeling programs themselves or other solutions, such as the photo editing of pictures with raster editing programs.

The problem of using multiple tools (other than the increase in the time and resources required) is the difficulty in obtaining uniform results between different instruments. By using various programs, the consistency of the outputs is often determined by the skills and experience of the designer.

1.4 Building Information Modeling

The lack of uniformity in the production of the documents, especially in the construction sector, can lead to significant difficulties, especially in larger projects. These differences can lead to misinterpretation of the data by the various work teams, which often causes delays, if not errors.

To stem this problem, since 2014, the European Parliament (*Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement and repealing Directive 2004/18/EC Text with EEA relevance*, 2014) has proposed (art. 22, sub. 4) that works of public interest be managed through the use of Building Information Modeling systems.

To limit the lack of consistency in the data of the lighting project, this too should be integrated within the scope of the BIM methodology (Guarini, 2020).

At the moment, this choice appears to be ideal for establishing guidelines for two reasons, the first relating to the specifically collaborative nature of this procedure and the second to the regulatory imposition on its use, which is increasingly growing in recent years, and it will be even more so in those to come.

Concerning the first reason, Information Modeling has as its fundamental principle the collection and sharing of information relating to the functions of the elements of the project. This information is available to all professionals in the different sectors involved, architects, structural engineers, plant engineers. Among these, lighting designers can also benefit from this sharing of information and, at the same time, contribute to the work of other studios. However, there is a problem related to the current state of maturity of the BIM methodology, not yet at its maximum level. A diagram developed by Mark Bew and Mervyn Richards (Succar, 2015) shows four levels of BIM Maturity (3+1). The chart shows the ability/possibility of the design/production chain to exchange digital information relating to the building is measured under construction.

- *Level 0* is characterized by the total absence of collaboration. The project is made only through 2D images, disclosed and consulted only through printed tables or pdf (or both versions simultaneously). It represents the first step from analogue drawing (drafting table) to digital drawing (CAD).
- *Level 1* adds the 3D dimension to the project drawings, but the sharing of information is minimal. These are disclosed only as paper or vector output, but the 3D model that generated them remains with the designer, who does not share it in any way with other operators. The documentation produced is mainly used for approval by the administrations.
- *Level 2* is the actual passage to the BIM procedure. All parties involved use their specific 3D model, but this time the information can be shared via export with a standard (ISO, 2018) file format **.IFC* (Industry Foundation Classes) (BuildingSMART, 2021). Other professionals can import this file type into their software in a consultative manner, that is, without modifying it but using it to check for any geometry conflicts and extrapolate the information of the individual construction elements. A limit for this BIM level is the need for a new export/import if there's a change to the original design. Nevertheless, this is the most common level of operation today, and lighting designers can benefit from this approach, albeit with the inherent limitations of this degree of maturity.

- *Level 3* is BIM in its full maturity as a collaborative methodology. Each designer works on a single shared model, which can also be consulted and modified by the other actors involved. This level has the undoubted advantage of constantly updating and validating data without the need for continuous exports and imports. All this presupposes the use of a single standard format. Unfortunately, due to the different software houses and the different disciplines involved, it is difficult to determine what this format may be, especially for commercial and copyright reasons. Due to these issues, this level has currently only been hypothesized and has not yet been reached.

The choice of opting for a BIM solution is, secondarily, dictated by the current regulatory framework (standard ISO/CD 19650:1-4), which will come into force after an initial legislative gap. Numerous states of the European Union have activated a roadmap that will lead to the mandatory nature of BIM practices in the context of tenders (EU BIM Task Group, 2018).

The Italian government, for example, has dictated through the so-called "BIM Decree" D.M.560 of 1.12.2017 (Ministero delle Infrastrutture e dei Trasporti, 2017) the time frame for the introduction of the mandatory use of this methodology in public works contracts that present an amount higher than a certain amount (standard UNI 11337:1-10). The application of the law was valid for projects over 100 million euros on 01 January 2019. The threshold is expected to decrease to 1 million euros in 2023, while from 2025, the obligation will be valid for all new public works, regardless of the amount.

1.5 Lighting in BIM software

Most software that implement BIM logics can read photometric files. As already mentioned, to use the software for project support, it is necessary to use virtual sources that can reproduce the correct distribution of light intensities (and not just represent an ideal source, as for OpenGL lights). These files report angular coordinates and the corresponding luminous intensity value. In doing so, it is possible to describe how light behaves in space.

In order to obtain these files, it is necessary to measure the luminous intensities of the luminaire (generally on an instrument called a goniophotometer). The measurement implies the use of a coordinate system (CEN, 2012). It is a set of planes with a single axis of intersection (polar axis) on which the photometric center of the luminaire lies. Two angles are required to determine a direction in space: the one between the reference plane and the following half-planes and the one between the polar axis and the direction considered. Generally, the most used reference system (especially in interiors) is called C-γ.

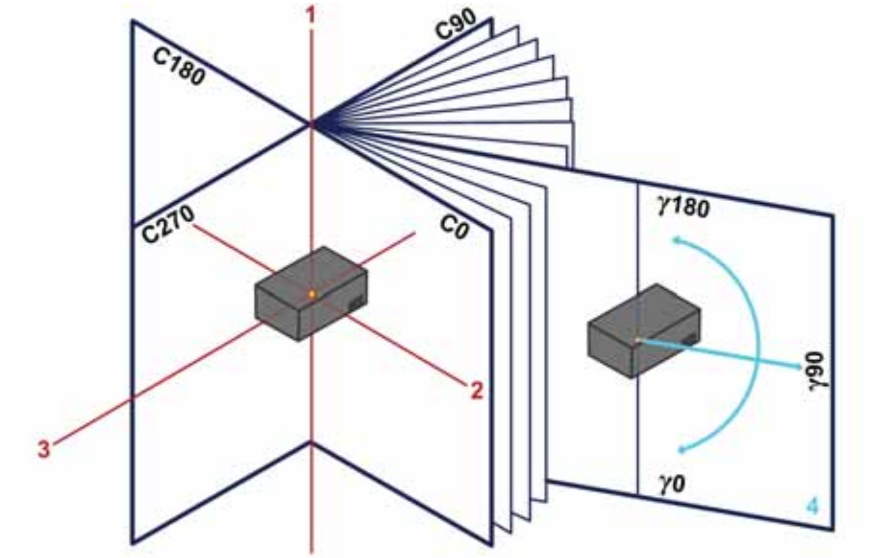

Fig. 1.6 - The C-γ reference system as described by the standard EN 13032-1: 2012. 1) Primary axis (polar). 2) Secondary axis. 3) Tertiary axis. 4) C-plane. The yellow dot represents the photometric center of the luminaire.

There are numerous formats for photometric files. The most universally accepted by many software packages is the IES file format, developed by the Illuminating Engineering Society (IES, 2021) and regulated by a specific standard, the ANSI/IES LM-63-19.

This type of file is generally read by BIM software, to name the most common: Autodesk Revit (Autodesk, 2021b), Graphisoft Archicad (Graphisoft, 2021) and Allplan (Nemetschek, 2021). However, there remains a problem related to the representation of the lighting fixture. Photometric files such as the IES do not contain detailed information regarding the geometry of the luminaire, representing it as a generic cube or cylinder capable of emitting light. In order to recreate a scene where lighting products are represented, this can be an issue. One can associate the photometric file with a 3D geometry that replicates the luminaire features. In that case, it is not uncommon to place the photometric center within the 3D geometry itself. The problem arises from the fact that, in this case, the distribution of light intensity could be hindered by the geometry, significantly interfering with the correct photometric simulation to be obtained (Siniscalco and Guarini, 2018). For example, some CAD software - like 3D Studio Max (Autodesk, 2021a) - contemplate this problem and offer a solution to avoid this interaction. There is the possibility of preventing the geometry from casting shadows when it is illuminated. In the case of BIM software, this solution is not available. However, it is possible to use plug-ins that solve the problem (in a different way) at the level of the rendering engine. Instead of excluding geometry from the projection of shadows, these plug-ins exclude the materials assigned to the luminaire's geometries. In order to operate this solution, the luminaires material must not be native to the BIM software but specific to the plug-in. An example of this approach is that of VRay for Revit (Chaos group, 2021).

1.6 The color of materials

A further problem to be faced in an attempt to reproduce the interaction between light and matter correctly is the Colour, Material and Finish (CMF) design simulation. Faithful reproduction can be achieved by using multiple devices, both input and output. This plurality of tools raises the problem of Color Consistency, which can be solved using Color Management (Rodney, 2005).

Acquiring the color of the same material with a scanner or a camera could lead to different digitization. Similarly, the display of the results of this acquisition can be perceived differently by the observer if this is done through a monitor or printer. It could be perceived differently even between two monitors of the same brand and model but with different settings. It can therefore be said that each hardware device has its own *color profile*. Furthermore, an acquisition device should be periodically calibrated to obtain a valid color profile. This because of many factors, like the non-immutability of the acquisition performance of the device.

The methods for performing this calibration can change between different devices. For example, for a camera, the procedure consists of framing a standard color palette within a shot relating to the finish. An example of these is given by X-Rite (X-Rite, 2021a). Through proprietary software or plug-ins for the most used photo-editing programs, it is possible to code the colors present in these palettes positioned within the shots and obtain the device's color profile associated with a specific lighting condition.

If the acquisition has to be done with a scanner, the procedure would consist of using another type of color table, like the ANSI IT8 (Coloraid.de, 2021) or the ISO 12461 (ISO, 2016). This calibration implies the color chart's acquisition without the actual sample that must be acquired. This is because, in the case of the scanner, the lighting conditions of the surrounding environment do not influence the result. To achieve that, the sample to be scanned must be kept in a standardized situation, like as inside the cover of the scanner which will be placed under a black cloth. Subsequently, a specific software generally supplied with the IT8 sample - like VueScan (Hamrick, 2021) - can generate the scanner's color profile.

The monitor on which the acquisition results are observed should also be periodically calibrated. In order to do this, there are various hardware solutions - like the SpyderX (Datacolor, 2021) or the ColorMunki Smile (X-Rite, 2021b) - with related software that guides the user in the calibration process.

Once the color profiles of the various devices have been obtained (called *relative* because they refer to specific hardware), the color consistency is obtained by making transformations between the various profiles and an *absolute* color space, independent of the device used.

The universal (and often unique) absolute color space managed by CAD software (and also the BIM ones) is the *sRGB color space* (Nielsen and Stokes, 1998). Therefore, to use colors as faithful as possible to those of the finishes, it is advisable to perform these transformation operations between the relative profiles and the absolute sRGB profile in photo editing software with an efficient and complete color management module.

1.7 Conclusions

Having found the best procedures to faithfully reproduce luminaires and the distribution of their luminous intensities and the color of the materials, it should be possible to produce images that are photometrically correct and also photorealistic. Furthermore, this goal should be achievable without worrying about embellishing the pictures with tweaks that would be denied during the realization of the project, causing a possible dispute with the end customer.

Lighting design software, as already mentioned, while providing photometrically correct results, do not generally reach adequate photorealism levels. The software commonly used in BIM procedures have the potential to satisfy both photometric and photorealism requirements (Murdoch, Stokkermans and Lambooij, 2015). However, working in a *BIM level 2* context and considering the collaborative nature (between different disciplines) of the methodology, a hybrid solution is usable. It is possible to leave the photorealistic rendering to the BIM modeling software, using specific plug-ins, and have the photometric verification and compliance with standards to the lighting design software.

The dialogue between the two software is achieved by exporting the BIM work file in the **.IFC* interchange format, subsequently imported into the lighting CAD.

Fig. 1.7 - Photorealistic image obtained directly in the BIM program with the help of a rendering engine plug-in.

A limitation to this approach is that it is impossible to make the most of the tools of the two types of software. Thus, for example, lighting design does not benefit from the interactive phase of the BIM methodology. At each modification of the architectural project, one is forced to modify the *.IFC file and redo the positioning of the lighting fixtures and other tools in the lighting software. Vice versa, once the lighting verification is done, to integrate the result into the architectural project, it is necessary to edit the BIM model by hand, reproducing the solution verified in the lighting CAD. In consideration of this, the design and verification of lighting would risk being relegated to the final stage of the process rather than evolving with it.

The continuous development of BIM software has led to the appearance on the market of numerous plug-ins capable of providing solutions. Concerning the aspects related to lighting, we can mention the cloud-based solution LightStanza (2021).

These plug-ins allow you to export the BIM model/database to the cloud by accessing it from a web browser. Thanks to this approach, the lighting design can be based on the luminaires included in the BIM database or possibly introduce new ones. In addition to the calculations (always in the cloud, decreasing the load on the computer), another novelty is the possibility of re-exporting the lighting solutions (calculations and documentation) from the lighting software to BIM in a simplified way.

In any case, given the high complexity of the problem and the tools involved, it is easy to understand that currently, a single and complete solution for the integration of the lighting project in the BIM methodology does not yet exist. But we expect, in the coming years and with the evolution of technologies, convergence towards a smaller and more efficient set of tools.

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2. Digital color acquisition and management of cultural heritage: from spectrophotometry to digital imaging

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Abstract

Color plays a fundamental role in cultural heritage applications. From frescoes to statues, from paintings to architectures, from photography to films, color is used to engage the public, communicate a message, and as a mean of expression of the artists. Although, the color sensation and perception derived from an object of cultural importance depend on the properties of the materials composing it, together with the spatial arrangement in which the colors are inserted and observed. When thinking about real objects, color is not just an esthetical element or only a mean of expression, but it is the consequence of the radiation-matter interaction, which is strictly related to the physical and chemical properties of the material. In this context, modern colorimetry became a fundamental science since the beginning of the last century, when it was first applied to industrial aims.

Moreover, since Human-Computer Interaction and computational power are becoming more and more essential in our daily lives, greater importance is given to the digital color representation and to the digital color imaging. In this way the development of instruments, measurement strategies, and tools that can correctly reproduce and represent materials, contrast, and colors as faithful as possible to the original objects is fundamental. The correct reproduction of the color of an object of cultural importance is necessary for many applications (e.g., the analysis of physical color, the light design study, etc.) besides the restoration, preservation, and valorization of the artwork itself.

In this essay, we will analyze the main limits of colorimetry as well as the current analytical techniques employed to digitally acquire the color information of physical objects for cultural heritage applications. We will focus on digital color reproduction issues, describing the importance and the difficulty of a correct illumination, and showing some practical examples of problems encountered in the color digitization workflow of physical color.

2.1 Introduction

The color of objects exists because of the interaction of three factors: the light source illuminating the object, the physical and chemical properties of the material composing the object itself, and the response of the Human Visual System (HVS) (Oleari, 2015). In this triangle, the objects are visible because of the wavelengths they absorb, reflect, or transmit depending on their chemical and optical properties. Then, color is created by our vision system through two mechanisms: the photons capture by cones (also known as quanta catch) and the spatial computation of the receptors' responses. Finally, the light source not only interacts with the object but also with the HVS, as it plays a vital role in the color appearance of objects through adaptation.

The science attempting to physically describe the human color perception with an objective numerical system is colorimetry. It was first introduced by Maxwell in 1862 and from the beginning of the current century it has played an important role in all areas that involve color generation, perception, and rendition. This is even true in the field of cultural heritage, where the introduction of colorimetry has allowed a multiplicity of applications.

Over time, if on one hand the spread of interest in the study of cultural heritage has led to the development of new non-invasive and non-destructive technologies for the analysis of materials, on the other hand this was not the case for color analysis. The colorimetric approach is still stuck to the traditional analysis since the beginning of the twenty-first century: conservation scientists exploit it only to assess the color of the materials studying their optical properties and without considering the psycho-physical aspects of color vision. In this way, color science still presents numerous open issues that have not been resolved yet.

The spread of the wide variety of digital technologies deeply contributes to increasing the application of colorimetry in the field of cultural heritage as well. The digital color reproduction of the objects of cultural interest to enable their preservation and valorization is the most common purpose in this context. The digitization of the archives is also becoming more and more prevalent and is highlighted by various national and international digitization campaigns. In this field, the complexities of a correct color acquisition and reproduction are largely well-known, but this becomes particularly dangerous and challenging in the case of cultural heritage.

Starting from the above considerations and aiming to grow awareness on the readers of this book, we organized the chapter into three sections: the first one presents a concise critical overview of some open problems in color characterization and measurements, the second part briefly presents the variety of color acquisition technologies and recording system; the third part introduces the most common problems encountered during digitizing cultural objects, describing the importance of instrument calibration, the difficulty of a correct acquisition due to several open issues (such as glare phenomenon, the impossibility to obtain a uniform illumination, the complexity of a real scene and its bidimensional representation), and the difficulty of proper color management.

2.2 Color formation and colorimetry

The concept of color is often entangled with colorimetry. To better understand how a correct description, measurement, and evaluation of color is achieved, it is necessary to briefly introduce the principles of colorimetry and color formation.

Two clear and complete critical overviews about these topics are (Rizzi, 2021a) and (Rizzi, 2021b).

In his works, Rizzi underlines that the HVS generates color sensation with two mechanisms: the photons capture by cones (i.e., the spectral radiance of a stimulus) and the spatial computation of the receptors' stimulation (i.e., the spatial arrangement of all the spectral radiances in our field of view). This means that color is not the unique product of retinal cone responses, since the local structures, such as edges and gradients, in the content of a scene change the final color sensation.

Since the high complexity of the HVS, color science has simplified the color sensation characterization limiting the effect of spatial mechanism. As a result, colorimetry works under the strong basic constraint of *aperture mode*, where a small color stimulus is isolated, and it is observed in a darkroom with no light. Based on this assumption, CIE XYZ is a pointwise colorimetric model in which the light responses of several stimuli do not interact with each other. This is deeply far from real situations and the contribution of the illuminant source and the objects are not distinguishable (see the scheme of Fig. 2.1).

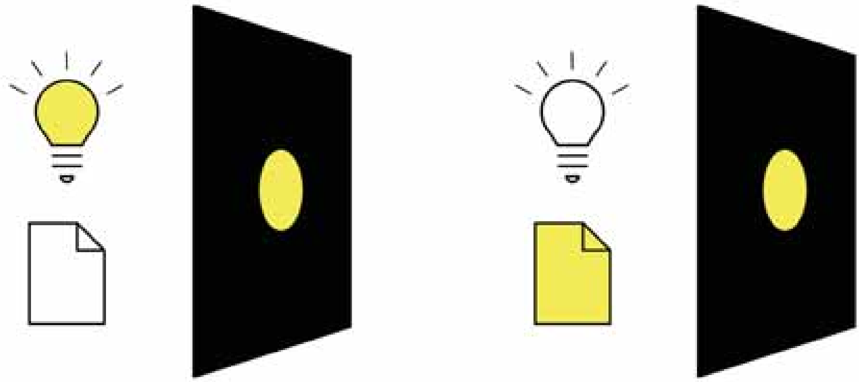

Fig. 2.1 - Aperture mode constraint: a white source illuminating a yellow paper (left) and a yellow source illuminating a white paper (right) generate the same color signal (Rizzi, 2021b).

This ambiguity is solved with the so-called "perceptual uniform spaces": CIE L*a*b* and CIE L*u*v*, which work in *object mode* (or *surface mode*), with the introduction of a reference illuminant. In this way it is possible to distinguish the exact color of a surface from the lighting source. Nevertheless, the color is still evaluated pointwise since spatial interaction is still not considered.

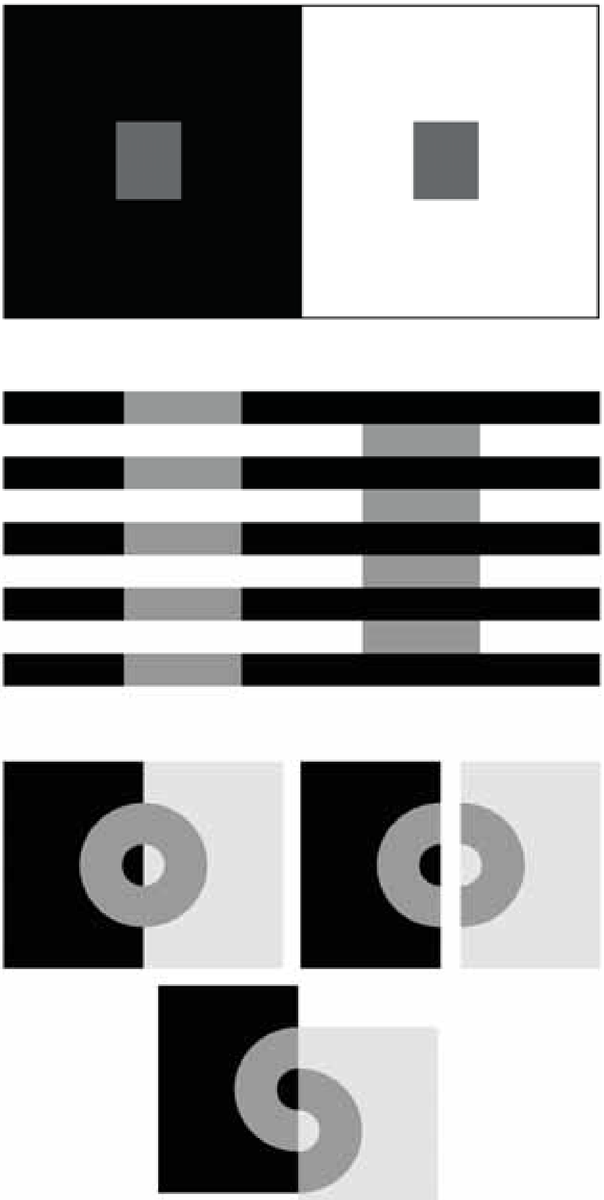

Fig. 2.2 – Example of visual illusions determined by the spatial interaction mechanism: simultaneous contrast (top), assimilation (center) and Kofka ring (bottom). (Rizzi, 2021a; Rizzi, 2021b; Koffka, 1935).

Fig. 2.2 shows some visual illusions that Rizzi presents in (Rizzi, 2021a) and (Rizzi, 2021b) as examples of the effects of spatial arrangement on color perception. On the top, the simultaneous contrast phenomenon, that changes the perceived brightness of the color in the center in conflict with the surrounding (the darker the background the lighter the center will appear and vice versa). In the center the assimilation phenomenon, that changes the perceived brightness of the color in the center accordingly to the surrounding (the darker the background the darker the center will appear and vice versa). Finally, on the bottom, the Kofka ring (Koffka, 1935), where the perceived brightness of each color changes according to the different edges. Even though the gray patches look different, their colorimetric values are always the same in every color system. This is because the difference in appearance is not caused by different stimuli but depends on different spatial arrangements of the scene.

Outside the *aperture mode* and *object mode* configurations, colorimetry has not been defined yet. A nowadays open issue is clearly the need to develop a model that includes the entire contribution of the HVS mechanisms, able to objectively describe the color from different fields of view and spatial arrangements.

2.3 Color recording systems

Systems for color information recording include both color measurement instrumentation useful for uniform areas of color and image capture devices designed to capture spatially varying color information.

Hereafter, the main technologies for color acquisition are introduced. For their technical operating principles, the readers may refer to the book (Sharma and Bala, 2017).

2.3.1 Spectroradiometer and spectrophotometer

The most direct and complete method for recording color information is to sample the spectral distribution. A spectroradiometer is a punctual device for sample surface inspection. It measures the power distribution of optical radiation (SPD) or the reflectance as a function of wavelength. Spectroradiometers employed for color recording usually operate in the visible region of wavelengths (ca. 360-780 nm) and have a spectral resolution of 1 to 2 nm.

A spectrophotometer is a punctual tool for measuring the spectral reflectance of an object as well, and, unlike spectroradiometers, it does not measure self-luminous objects since it features an inbuilt internal light source that illuminates the sample under measurement.

Both devices are useful for the color calibration of printers and scanners as well as for determining the color characteristics of objects. In the field of cultural heritage, they are usually employed for the identification of organic and inorganic materials like dyes and pigments (Bruni *et al.*, 2002; Bacci *et al.*, 2003), especially when a database of frequently used pigments is available.

2.3.2 Colorimeter and photometer

A colorimeter is a punctual device that exploits trichromacy as color values in CIE XYZ, CIELAB, or other color spaces. Some colorimeters have an inbuilt light source (sometimes few different illuminants are available) for the acquisition of color of reflective objects, whereas others measure only self-luminous or externally illuminated objects. This type of instrument is less expensive than spectrophotometers and spectroradiometers since it does not provide detailed spectral information. It is less accurate and measures only color tristimuli offering an acceptable color performance and significant speed advantage in addition to lower cost.

In the field of cultural heritage colorimeters are widely used in many applications, e.g., the study of color aging and degradation in relation to different parameters such as temperature, humidity (La Gennusa *et al.*, 2005), illumination (Zhao *et al.*, 2019), (Dang *et al.*, 2018), and/or microorganisms presence (Rosado *et al.*, 2019); the production and testing of new protective and cleaning products, which do not cause a chromatic alteration of the surfaces (Giorgi *et al.*, 2002), (Bartoletti *et al.*, 2020); the color matching for restoration purposes; and so on.

Photometers are single-channel devices that provide a measurement of the luminance of a self-luminous or externally illuminated object. It is usually employed to inspect the power spectral distribution of illuminant sources.

2.3.3 Digital color cameras and color scanner

Color recording devices such as digital color cameras and color scanners work on similar principles, but their intended uses are somewhat different. Both tools capture color data by acquiring the picture through a series of color filters having a different spectral transmittance and sampling the colored resulting images with electronic sensors. Digital color cameras are meant to take color photos of the real-world scene in the same way that traditional cameras do, with the exception that the images are captured electronically rather than on film. The lack of control over scene illumination is one of the issues of color capture that color cameras face more than scanners and colorimeters.

Scanners are usually designed to scan images printed on paper or transparencies (like documents, photographs, and films), and they feature an inbuilt light source. These devices do not need to capture the complete image in a single exposure like digital cameras do, thus a single sensor per channel is scanned across the image to enable spatial sampling. The use of a single sensor simplifies and improves the performance of the device, as well as allowing the use of more expensive and precise sensors.

2.3.4 Multispectral and hyperspectral imaging

Multispectral imaging is a technology that acquires an image in which each pixel has several channels carrying spectral information. Multispectral images cover a wide range of image types, from the common three-channel color images to hyperspectral imaging with hundreds of bands. Thus, the data provided by the hyperspectral imaging technique are the so-called *datacube* or *hypercube*, which contain data represented in three dimensions: two dimensions describing the spatial location, and a third spectral dimension representing a continuous spectrum (in the case of multispectral images, the third dimension represents a discrete function). Thus, hyperspectral imaging mixes the power of spectrophotometry whit the power of imaging technology. It is a non-invasive and non-destructive technology that allows us to obtain in a single shot thousands of radiance spectra of the object under analysis, one for each pixel of the image. These devices are not limited to the visible range of the electromagnetic spectrum, and they commonly operate from the UV to the infrared regions, usually ranging from 400 to 1000 nm.

Traditionally, multiband sensors were born for remote sensing applications, and only in the last twenty years they have been employed for the analysis of historical and cultural objects, e.g., for the exploitation of underdrawings in paintings (Walmsley *et al.*, 1994); the characterization and mapping of pigments and inks in painted artifacts and drawings (Casini *et al.*, 1999; Baronti, Casini and Porcinai, 1998); the studying of unreadable scrips revealed (Bearman and Spiro, 1996); the digitization purposes (Lahanier *et al.*, 2002; MacDonald *et al.*, 2017); and many others.

For further details, the readers may refer to (Fischer and Kakoulli, 2006).

2.4 Digital color reproduction issues

In order to process digital color images or 3D reconstruction, the object must be sampled both spatially and spectrally, acquiring their spectral radiance or reflectance distributions. To achieve this purpose, defining a standard acquisition protocol is mandatory not to run into wrong sampling, affected measures or bias. This is also true in the field of historical and cultural heritage and especially for photographic and audiovisual materials. Nowadays museums, libraries, and archives (where this type of material is usually stored) are indeed promoting digitization campaigns to allow wider access and fruition to the public to their collections.

Despite the existence of many regulations provided by national and international institutions, like the Italian ICCD (Istituto Centrale per il Catalogo e la Documentazione) (MiBACT ICCD, 1998) or the European FADGI (FADGI, 2015) and Metamorfoze (van Dormolen, 2012), the guidelines are usually not enough to carry out a correct and accurate digitization. Most of the problems, usually resolvable by simple precautions, are rarely mentioned in the regulations. Furthermore, the operators that perform the digitization are often not aware of all the risks of wrong color reproduction and an evaluation of instruments performance is rarely considered, as well as an objective evaluation of the quality of the results. As a consequence, an uncontrolled application of automatic operations without an accurate knowledge of the algorithms and corrections introduced can indeed produce errors in the acquisition, which can lead to issues in managing data.

Hereafter, in the next subsections we list a set of the most common issues that can be found along the digital color reproduction workflow. There are no solutions to overcome the presented problems; instead, the focus is on describing issues and the questions they raise.

2.4.1 Calibration of the instruments

One of the main open issues is the calibration of the instruments. Scanners and monitors are quite always not sold with adequate calibration tools, like for example the IT8 targets. Furthermore, most of the time calibration operations are not included in the acquisition process described by the national or international protocols, and all results in a high risk of scanning materials without any calibration.

2.4.2 Optical veiling glare

Another fundamental problem is instrumentation errors such as the transmission of frequencies, the aberration, and the formation of glare. These errors are caused by the presence of lenses inside the acquisition instruments themselves, which alter the information reaching the sensors. Optical veiling glare is indeed a light reflection-based phenomenon that consists of an unwanted light-spread on the imaging sensors. As a result, it produces a loss of information and a decrease of the dynamic range of the image acquired, so that the resulting digital image always has a different contrast from the original one. Even though the glare problem is well known in the field of lens design optics, it is much less studied and considered in the imaging field. Measures and tests of glare in image acquisition systems started indeed only some years ago (Signoroni *et al.*, 2020). Unfortunately, glare is not just noise but is a systematic distortion of the acquired data. The values at each point of the scene are affected according to their spatial arrangement and magnitude, making this phenomenon scene-dependent and exposure time-independent. (Gianini *et al.*, 2019) discusses the main reasons why glare cannot be easily removed in the image acquisition process.

An example of application in the field of cultural heritage is the assessment of the presence of glare also in hyperspectral imaging techniques (Sarti, Plutino and Rizzi, 2020).

Glare also affects our vision since human eyes are equipped with lenses as well. Despite the loss of contrast in the retina can be severe, spatial comparisons counteract the glare phenomenon. As a result, the HVS is much more robust than any color recording system based on traditional colorimetric approach due to the spatial mechanism of vision. Therefore, the pointwise colorimetry cannot overcome the limits imposed by the instruments and the problem of a correct image acquisition is still open.

More detailed information on glare can be found in (McCann, Vonikakis and Rizzi, 2017).

2.4.3 Non-uniform illumination

Colorimetric pointwise approaches for predicting color appearances are not applicable in complex-scene with non-uniform illumination. Unfortunately, uniform lighting distribution does not exist. Every point in a scene is likely to have different levels of illumination, which can have a big impact on the color signal and appearance. Moreover, while the human eye adapts to the scene, providing a visual appearance that is mostly independent of the scene illumination, cameras lack these adaptation mechanisms, resulting in imaging with significant color casts and shifts.

This is a very complex open issue that in the field of cultural heritage, is not only concerned with digital color acquisition purposes, but it is also a well-known problem in the definition of an optimal illumination for the valorization and the fruition of the works of art, especially for museums and collections. Every exhibition needs a trade-off among three factors: the visitors, the cultural assets, and the architecture of the building that hosts the event (Berns and Grum, 1987; La Gennusa *et al.*, 2005). First of all, the contribution of the light must be specifically designed for the exhibit since it can affect the experience of the public. Nevertheless, the illumination system must not damage the work of art. Because of this, the museum personnel must also consider the specific national and international regulations that define the condition of the range of intensities and the amount of light per year the historical material can tolerate – as an example see Italian regulations for museums in (MiBACT, 2000). Unfortunately, due to the nature of the buildings within which the museum is located, the lighting conditions cannot always be controlled. The buildings themselves can be considered historical monuments under the Cultural Heritage regulations. This means that they are not allowed to be changed or modified as well as the windows cannot be obscured by curtains or shutters to not modify their architectural appearance. For instance, many exhibition rooms are hosted inside ancient buildings such as old castles, monasteries, or factories, which may have large windows that provide natural light to the entire room. As a result, the light variation during the day can significantly affect the design of the exhibition and cause sensitive materials to fade and degrade more quickly (Gunde, Krašovec and Platzer, 2005).

In this unstable balance, the adequate assessment of the color rendering of the work of art is effectively hard to manage. This is also aggravated by the lack of guidelines and objective metrics related both to the final color perception of an object in a complex spatial arrangement and to the spatial distribution of the illumination. A light source is indeed characterized only by its spectral power distribution (SPD), which provides no information about its spatial arrangement. The other important metric is the Color Rendering Index (CRI) (CIE, 1987), which tries to objectively define the quality of a light source by comparing its SPD with an ideal reference illuminant. Even though different rendering indexes have been introduced during the years, CRI still presents some criticism, especially for lighting systems with spiky emission spectra such as LEDs. The computed colorimetric value of CRI is indeed not always in line with the perceived final color evaluation. As a result, the chromatic rendering decision is usually left to the subjectivity of the curator of the museum or the light designer.

2.4.4 Complex real scene

Several parameters can affect the final color perception of a complex scene, such as the illuminant spectral and spatial distribution, the geometry of illumination, the observer's point of view, and, above all, the shape and the size of the objects. The non-correspondence between computed and perceived color can be observed using different color recording systems. Data acquisition tasks can indeed have some criticisms like the inappropriate measurement conditions. As already said, the colorimetric approaches of *aperture mode* and *object mode*, constrain the acquisitions to precise standard parameters of geometry of illumination, direction of observation and light source. Outside these conditions, traditional colorimetry will usually fail. This is the case of complex 3D real scenes.

For instance, an application that remarks the limits of pointwise colorimetric measurements is the color evaluation of gemstones (De Meo, Plutino and Rizzi, 2020). Even though their color assessment is a key factor for determining the market price of a gem, defined standards and guidelines for their color evaluation still have not been introduced yet. Furthermore, the lack of a commonly shared protocol, the refractive properties of these materials make the task even harder because of the extremely complex measure condition. The objective colorimetric measures have indeed provided different results compared to the subjective human eye evaluation, which instead reached the highest precisions. As a result, the color assessment of gemstones is still visually performed by experts.

Other applications in which the human eye evaluation still provides better results are, for instance, the color assessment of materials under LEDs illumination; the hair color evaluation; the variation assessment of color after restoration work. In all these cases pointwise approach fails because it tries to compute a color evaluation of a complex contest without considering the spatial processing of vision.

2.4.5 Bidimensional representation of real scenes

All the problems mentioned above are valid not only for image or film digitization but also for 3D reconstruction purposes. The creation of the 3D digital model consists of acquiring images or scans of the object under analysis from various points of view and then merging the information into a single digital model consisting of a dense cloud of points or a set of triangles. Thus, 3D acquisition consists of the creation of a three-dimensional digital model that faithfully represents the shape and color characteristics of an object. In practice, the 3D digital model is an accurate description of the surface of the object under examination. Since the starting point of this technique are still images, the targets and tools available for calibration, contrast correction, and color management are the same. However, there is also another important complexity to deal with: when acquiring an image, a 3-D object scene is projected into a 2-D representation, but a bidimensional representation of a real scene is not the same as looking directly at the 3-D object (Rizzi, 2021b).

2.4.6 Color management

Once images are acquired, colors are a fundamental parameter during data processing since they influence the results of the algorithms. Usually, a color image processing pipeline follow the following steps: (a) exposure estimation, (b) pre-processing (e.g., noise removal), (c) linearisation, (d) dark current compensation, (e) flare compensation, (f) white balance, (g) demosaicing, (h) color transformation (in unrendered and rendered color spaces), (i) post-processing (Plutino and Simone, 2021; Ramanath *et al.*, 2005).

While the pipeline structure is generally standardized, each step can be carried out using a variety of algorithms, metrics, and measurements based on several reference targets, like the ColorChecker, the SFR, or the IT8. In addition, the quality of several features, such as color reproduction, noise reduction and edge preservation, can be assessed by the system performance evaluation. As a result, each pipeline is unique for its specific application field.

The ColorChecker is one of the most common targets for image correction in image processing and photogrammetric pipelines. This chart, which was first introduced in 1976, is nowadays employed in photography, scanning, and object acquisition to check color stability. However, several color reproduction errors may occur, and several studies proved the ColorChecker to be insufficient to ensure color reproduction robustness. As a result, the entire photogrammetric process, as well as object digital reconstruction, may be biased and not faithful (Gaiani *et al.*, 2017).

Cultural heritage digitization differs from other imaging applications because aiming at future repurposing and durability. Therefore, in this domain it is crucial not to lose information, and the digitization process must provide digital images perceptually faithful to the original object, rather than pleasant. As a result, contrast and color reproduction cannot be approximated, and inaccuracies must be kept to a minimum and constantly monitored. Several image quality assessment methods and many difference/quality measures have been introduced to achieve a faithful digital image, but they are still dependent on pointwise colorimetry (Barricelli *et al.*, 2020). As already underlined, pointwise-based colorimetry has been proven to be still unable to reproduce colors accurately and fails in complex scenes with non-standard expositions and with different light sources. The digital acquisition system and technologies at current reading are still not sufficient to guarantee a faithful reproduction of the historical and cultural assets, thus new solutions are required.

2.5 Conclusions

In this chapter we have underlined and recalled the assumptions and constraints beyond colorimetry, which are often not considered or even not truly understood. Their description can help in comprehending possible mismatches between computed and perceived color sensations in many applications.

The description of the current analytical technologies employed to analyze color information was meant to show the wide applications in which colorimetry can support the study of historical and cultural object, as well as to facilitate the explanation of the most prevalent and challenging issues among all the color digitization pipeline.

Color analysis and reproduction work fine in *aperture mode*, but still fail outside pointwise colorimetry constraints and are often substituted with subjective assessment. There is the need to develop new methods for computing color mechanisms in complex scenes, that is, considering spatial interactions, and not just input signal of cones.

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3. Strengthening knowledge of the transition to a circular economy in the furniture sector

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Abstract

This chapter focuses on thematic areas of the circular economy, reflecting the goals of the European Green Deal and addresses gains made by European furniture companies. The goal is to explore guidelines and assessment criteria for how the design and manufacturing of furniture can contribute to a climate neutral Europe by 2050 with a sustainable economy that leaves no one behind. How are European furniture companies adapting to a circular economy model?

A circular economy aims to preserve the value of products, components, and materials within a larger economic system. It is oriented to achieve more efficient production and consumption systems, thanks to continuous and regenerative cycles. It also focuses on reduction of raw materials and energy consumption, waste, and emissions generation in the production processes. The adoption of the circular economy requires a change of business, territorial, and individual visions, and to rethink ways of producing and consuming.

The authors study evidence of the circular economy values, such as reuse, recycle, remanufacturing in the European furniture sector. By developing the knowledge base for greener and smarter manufacturing processes, it is possible to plan for a sustainable and more democratic European design culture.

3.1 Introduction

This chapter focuses on circular economy (CE) strategies in the furniture sector and offers examples where furniture companies in Europe are responding to the transition. We explore the values of the CE model and identify strategies for European furniture companies to shift to a more socially democratic, healthier, and sustainable future. Which companies are leaders and innovators of CE solutions and strategies? By strengthening the knowledge base for greener solutions and CE manufacturing processes, it is possible to foresee a sustainable and more democratic European design culture achieve the goals outlined in the European Green Deal.

Furniture relies on materials and energy for its manufacturing and distribution to consumers throughout the world. Across the sector, manufacturing utilizes a hybrid of analog and smart digital technologies that result in making innovative solutions, systems, and services. The origin of the word *manufacturing* connects production to a process of making with one's hands using hand tools. The term has Latin origin, a noun, denoting something made by hand; from French, reformed by association with Latin *manu factura* 'made by hand' (Etymonline, 2021). In the past 50 years, there has been an accelerated transition towards technological innovation in how most furniture is made, transitioning away from hands to machines, and more recently, to CAM technologies and digitally programmable robots. How things are made is the basis of manufacturing, but now, more than ever, manufacturing needs to be reconsidered in tandem with an important environmental challenge: Will the world be *made* a better place to live in tomorrow, by how things are made today?

We need to consider sustainable practices in using materials and smart processes that consume less energy in the resource extraction, transport, manufacture, and distribution of furniture products. Manufacturing has a profound impact on the health and welfare of those who make and use furniture, but also impacts the planet and environment regarding the energy consumed in the extraction, use, and reuse of materials and products. We begin by introducing environmental and economic challenges and an innovative program titled the European Green Deal. This is followed by a discussion of what is a circular economy. We then assess the global furniture industry and highlight European furniture companies adapting to this changing direction.

3.2 Background to the European Green Deal

The world today is facing complex environmental, societal, and economic challenges. The intersectionality of these challenges: climate change, environmental concerns of sustainability, health, and welfare issues, growing populations and urbanization, financial crises, shifts in societal lifestyle and values, and the rise of smart and digital IoT technologies, all contribute to the need to pause and reflect on the influence that manufacturing solutions, systems, and strategies can have on our lives. Manufacturing depends on designers and companies who address these realities and relies on consumer's buy-in to gauge successful outcomes. Smart strategies can serve as a foundation for innovative manufacturing strategies and solutions that benefit society, regional and global economies, and the environment. There is a need to develop further guidelines, and utilize assessment criteria for CE manufacturing, specifically by leading European furniture companies to help achieve climate neutrality with a sustainable economy by 2050. The European Union has begun that process.

On 11 December 2019, the EU Commission announced the European Green Deal (EU, European Commission, Secretariat-General, 2019) to transform the EU into the first climate-neutral continent by 2050. The plan is to improve the EU's economy, by turning climate and environmental challenges into opportunities. It is a growth-strategy to transform the EU into a more sustainable, more environmentally respectful place of production and consumption by adopting the CE model. The Green Deal's goals should result in a competitive circular economy, where there are no net emissions greenhouse gases by 2050, economic growth is decoupled from resource use, and no place is left behind.

Following the creation of the European Innovation Council (EIC), the European Commission launched a €1 billion call for research and innovation projects that: respond to the climate crisis; support the European Green Deal initiative; and help protect Europe's unique ecosystems and biodiversity. These initiatives were conceived before the COVID-19 pandemic. The Horizon 2020-funded European Green Deal call was created to spur Europe's recovery from the COVID-19 pandemic by stimulating transformative "green" challenges into innovation, opportunities, and solutions.

3.3 Overview of the Circular Economy

The CE model is gaining interest as a new industrial paradigm which demonstrates a smarter alternative to the linear economy (Murray, Skene and Haynes, 2017). The primary goal of a CE is to decouple economic growth from natural and limited resource constraints and connect the benefits of multi-use to proven sustainable practices. Therefore, the definition of the CE that best explains this research is:

> A sustainable development initiative with the objective of reducing the societal production-consumption systems linear material and energy throughout flows by applying material cycles, renewable and cascade-type energy flows to the linear system (Korhonen *et al.*, 2018).

The CE model is a smart approach to design, production, and consumption. It contrasts with the existing model of production and consumption identified as a linear economy. The linear economy is a process of making, using, and discarding products. It has been the paradigm for most worldwide industrial output, including the manufacturing of furniture. CE is an industrial system of manufacturing, distribution, and consumption that is restorative and regenerative by design. The term *restorative* suggests a closed-loop cycle that encourages more output and utility from products than what is delivered in a linear economy. In a restorative system, technical materials and products are recovered and given new life. In a regenerative system, biological nutrients are reproductive (Ellen MacArthur Foundation, SUN and McKinsey, 2015).

CE is not a new concept, but it has taken time to develop a conceptual framework with obtainable goals. A goal of CE is to extend the life and value of furniture through innovative manufacturing processes enabling reuse, repair, refurbishment, and remanufacturing cycles in production strategies that respond to environmental challenges outlined in the European Green Deal (2019).

In striving for a holistic and theoretical understanding of circular economy implementation, the authors leverage some of the consequential literature produced thus far (Simmonds, 1862; Ayres and Kneese, 1969; Kenneth E. Boulding, 1966; McDonough and Braungart, 2003; Lewis and Slack, 2014; Ünal, Urbinati and Chiaroni, 2019) and the CE research, publications, and video presentations executed by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2013). This collective research has helped frame options available to transform many industrial practices currently dependent on exploitation.

The novelty of CE relies upon a system where products are designed and manufactured to be used longer, applying any number of "value cycles" or closed-loop strategies to extend the value of the product beyond its conventional end-of-life (EoL) use (Ellen MacArthur Foundation, 2015). CE is a change in thinking in the approach to how we think about making things. It is a concept that puts [re] in front of use, make, and manufacture, placing value on innovative ways to re-use things. It is valuable and complementary to the Cradle-to-Cradle (C2C) concept (McDonough and Braungart, 2003). C2C has influenced thinking about values in design and manufacturing and has set the stage for today's discussion on the CE.

> Our goal is a delightfully diverse, safe, healthy, and just world, with clean air, water, economically, equitably, ecologically and elegantly enjoyed (McDonough, 2007).

This statement presents a new connection to why we design and make things.

The Ellen MacArthur Foundation developed a diagram that illustrates two intersecting economic systems, (liner and circular). Figure 1 illustrates two closed loop cycles located in distinct sectors: one biological and the other technical. The central vertical axis represents the linear economic model, while the rest of the diagram illustrates the continuous flow of materials and processes referred to as *value cycles.* The furniture sector is concerned with technical cycles. Including both biological and technical systems remind us that the furniture sector can draw values from both. Any one of these value cycles can extend the life of a product. A combination of value cycles manifests a traceable impact on the economy and the environment. These two models are often defined as cradle-to-grave (linear economy) versus cradle-to-cradle (circular economy) (Ellen MacArthur Foundation, SUN and McKinsey, 2015).

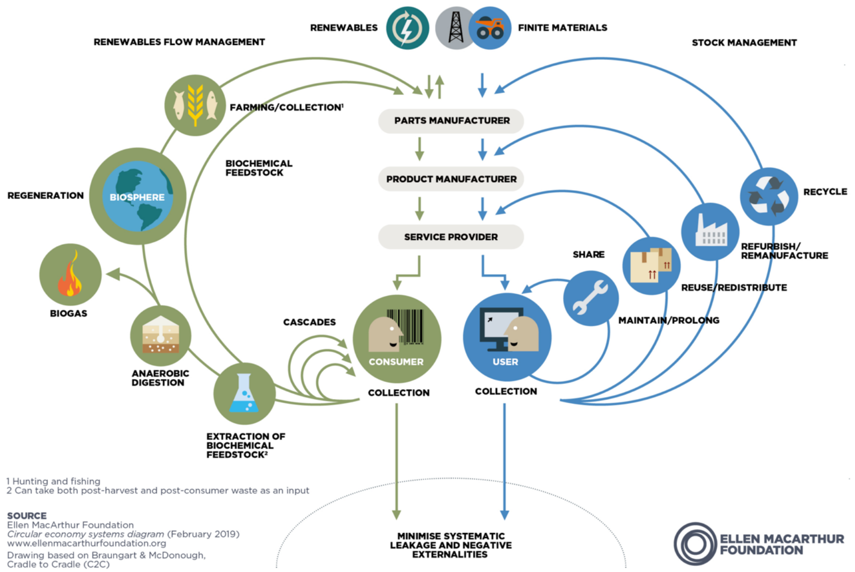

Fig. 3.1 - The Butterfly Diagram for Circular Economy. Circular economy systems diagram. Ellen MacArthur Foundation (2019). Drawing based on Braungart & McDonough, Cradle to Cradle. Copyright © Ellen MacArthur Foundation (2019), www.ellenmacarthurfoundation.org.

Addressing the critical problem of natural global resource depletion, the Ellen MacArthur Foundation (2013) has summarized four principles of the CE as "*points of action*" to revitalize existing material value throughout one or more stages in the manufacturing of products. The authors see value in the four principles and will later synchronize them to exemplary cases. It is important to note these are complementary, yet distinct from green and sustainable principles. Subcategories

(*) have been added by the authors to the four *points of action* related to the furniture sector:

1. Optimize the use of resources and energy throughout all life cycle stages.
   * Design for efficiency in the use of material, time, and energy.
2. Maintain production and components in use over a longer time.
   * Improve furniture design by thinking about modularity, standardization, and compatibility with existing components and assemblies (open platform).
   * Generate personal attachment to furniture.
   * Manufacture for self-maintenance and repair.
   * Consider ease of disassembly and reassembly.
3. Cycle materials through the production system as many times as possible.
   * Create opportunities for upgrading downgrading, adaptability, reuse and repurpose.
   * Consider the recyclability of material.
4. Utilize pure materials to improve quality of post-life use.
   * Use materials that maximize reliability and durability.

CE achieves more efficient production and consumption outcomes by moving products and components through continuous use cycles so that at the product's EoL there is minimum residual of a product that ends up as waste or in a landfill (Rios and Charnley, 2017). CE focuses on ways to re-cycle a product through stages of production to exploit all its reiterations of use. The full adoption of the circular economy within an industry requires a change in how society thinks about value and accepts new ways of consuming products through various cycles.

Cyclical, closed-loop processes allow for a broad range of strategies and actions for furniture such as:

- Refurbishing: remanufacturing a product to optimize its life.
- Restoring: refinishing or re-upholstering to extend the condition of a product.
- Repairing: corrective repair of a product.
- Maintaining: preventative maintenance to maximize product life

- Reusing: redistributing products through a change in ownership.
- Repurposing: changing the functionality of a product, (i.e., a chair becomes a table).
- Recycling: recovering the value of materials and components in products for reuse.
- Regenerative: a process of regrowing (renewing).

A CE is suitable for technological industries to adopt because it opens avenues for smart and innovative ways of using closed-loop processes. Also important is the reduction of raw materials and energy consumption, waste, and emissions generation in the production processes. Adopting the circular economy model does require a change in business practices and consumer behaviors. CE requires everyone to rethink the way products and services are produced and consumed. We examine the CE paradigm by applying the concept to the furniture sector to examine how well a CE can change an existing linear economy.

3.4 Overview of the Global and European Furniture Sectors

The furniture industry today accounts for a considerable portion of regional and global trade with approximately one million workers employed in the EU (EEB, 2017). The global furniture market was estimated at approximately €285 billion in 2019 and is expected to reach approximately €390 billion by 2026. Approximately one-quarter of the world's furniture manufacturing occurs within the EU28 member states, representing a €84 billion market that equates to a EU28 consumption of about 10.5 million tons of furniture per year (EU FURN360, 2017).

So often the case, after furniture no longer serves its primary purpose, if not sold to another user or repurposed for another use, it is discarded for any number of reasons into a landfill. According to the European Environment Bureau (EEB), 10 million tons of furniture are discarded by businesses and households as waste every year (EEB, 2017). This accounts for over 4% of the total Municipal Solid Waste (MSW) stream in the EU. Sadly, 80 to 90% of EU furniture waste in MSW was incinerated or sent to landfill with only 10% recycled (EU

FURN360, 2017). Waste arising from commercial sources is assumed to contribute 18% of total furniture waste generation across the sector. These numbers represent a cradle-to-grave life cycle: an unsustainable ecosystem.

In 2017, most of the EU furniture companies in the sector were small and medium-sized enterprises (SMEs). Italy (€17.5 billion), Germany (€14.5 billion), and UK (€8.8 billion) were the most significant furniture producers by value (EEB, 2017). The most significant exporters were Germany (€9.5 billion), Italy (€9.2 billion) and Poland (€8.7 billion). The largest importers were Germany (€11.8 billion), UK (€6.6 billion) and France (€6.0 billion). European member states are major consumers of furniture with a considerable proportion from wooden furniture, kitchen units, and mattresses.

The statistics on EOL production and waste are not limited to the EU. Historically, the furniture sector has utilized a traditional business model that follows a linear process: one of harvesting materials, making, using, then discarding products as waste. Waste is often burned or ends up in landfills, characteristic of the cradle-to-grave model. Additionally, this sector is known to use virgin raw materials (wood, stone, textiles) for production and uses adhesives, dyes, and coating materials to finish and protect furniture, which can result in emission of volatile organic compounds (VOCs). Regardless of the material consumed and technology used in the manufacturing of furniture, companies that focus on CE methods are reimagining the value of furniture by incorporating closed-loop cycles. We now explore tools and resources that provide opportunity and evidence of transition from a linear to the circular economic model.

3.5 CE Resources and Tools Available for the Furniture Sector

Resources and tools are available to advance sustainable furniture design, serving to build adoptable strategies and strengthen knowledge in the sector. Annotated projects also help benchmark sustainability. One project was coordinated by Centro Legno Arredo Cantù (CLAC) Ecomind (Centro Legno Arredo, Material Connexion and Istituto

Europeo di Design, 2006). It was the result of collaborative work that highlights ecological furniture solutions and material strategies. A second is Eco-Design (Fuad-Luke, 2010), cataloging a broad range of product and furniture solutions designed for a sustainable future. Both sources strengthen knowledge about sustainable and eco-sensitive strategies that benefit the environment and argue that eco-sustainability criteria should receive the same weight as technical, functional, aesthetic, ergonomic and economic considerations in the design process. Surveys and assessments serve as measurements of practice and attitudes that assists the adoption of a sustainable, methodological, design approach for innovative solutions in the various stages of the product life cycle is the adoption of the Life Cycle Assessment (LCA) (Ceschin and Gaziulusoy, 2016). The Ecodesign Directive by the European Commission (EU, 2005) provides directions for companies to use LCA to evaluate their productive processes and products. This self-evaluation tool helps identify CE practices being used and suggests others to incorporate in practice. This is a CE approach that many companies in the wood furniture sector can adopt to raise quality standards and be more competitive in a market that is increasingly attentive to the use of energy, materials, and certifications. The link between sustainability and innovation, in fact, is becoming increasingly intertwined.

A report from Federlegno Arredo (FederlegnoArredo, Symbola, 2016) highlights latest trends in the production of the furniture sector among leaders in the European market. It reports on low energy consumption, reduction of emissions, waste reduction, and recycling of materials. Furniture enterprises are identified by their green practices.

In recent years legislation at the European and international level has defined rules for the certification of raw materials from responsibly managed and environmentally sustainable sources. Among the most important are the Programme for Endorsement of Forest Certification (PEFC) schemes and the Forest Stewardship Council (FSC). These programs guarantee that the raw material used in the manufacture of furniture comes from controlled cultivation of plants, guarantees protocols that avoid deforestation, (the consequent increase of CO_2), and commits to maintain biodiversity in the areas of origin. According to the directives of the European Regulation 995/2010 (EU, 2010), materials are verified and certified, defining their origin and adherence to the standards provided. Furniture manufacturers and designers who source certified raw materials can add the endorsement programs to their marketing materials.

From the circular economy perspective, designers can use an eco-sustainable approach to design using strategies that consider varied factors in product development (Pigosso, McAloone and Rozenfeld, 2015). Not only by focusing on the formal and material characteristics of a sustainable product, but also considering the link between the product to other product processes such as packaging, distribution, marketing, and social performance. This business solution at the design phase can impact waste issues in localized markets. Chiu and Kremer (2011) provide an exhaustive analysis of Design for X guidelines and a toolkit, where X stands for any attitude in the design process (Manufacturing, Assembly, Disassembly, Logistics, …) to supply practitioners with an index for each DfX concept and method. In summary, a variety of resources and tools have been developed to strengthen CE knowledge in the furniture sector. Undoubtedly, there will be more to come. The next section explores the *Points of Action* outlined in the Overview of CE section and synchronizes them to innovative case studies.

3.6 Case studies and practices: innovative CE solutions and strategies

There is growing evidence of furniture designers and companies adopting CE values to improve furniture design and manufacturing processes. In this section, we provide examples which align with the previously identified four *points of action* that were discussed in 3.3 Overview of the Circular Economy. These furniture solutions and manufacturing companies exhibit substantial effort to commit to the CE value system. Following are six examples of innovative CE solutions and strategies that represent changes the furniture industry is making to extend material value and reduce consumption of energy throughout one or more stages in the manufacturing of furniture products.

3.6.1 Optimize the use of resources and energy throughout all life cycle stages

Companies in the furniture sector are seeking opportunities to optimize the use of resources and energy. The examples that follow were selected because they demonstrate forward thinking solutions for the management of resources and energy in manufacturing and distribution.

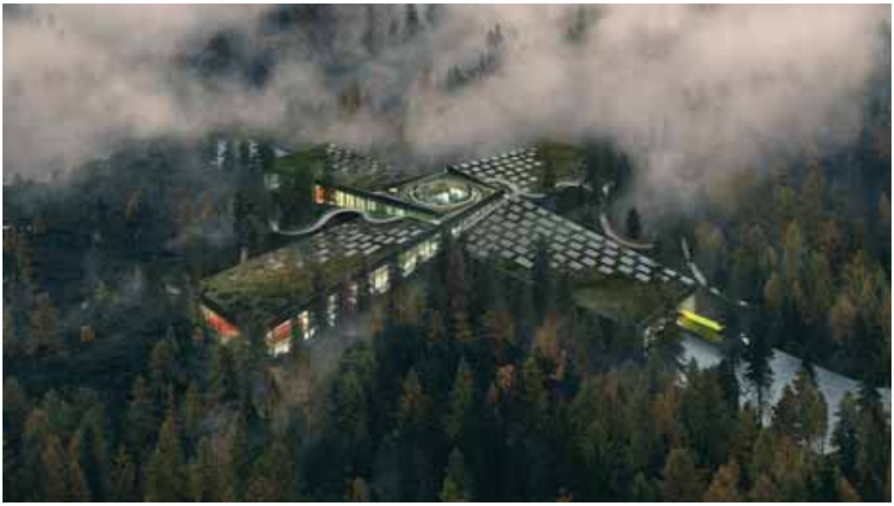

Fig. 3.2 - The Plus has been designed by BIG - Bjarke Ingels Group (2021) based on sustainable and CE values. The Plus Aerial Image credit: Lucian R.

Vestre is a Norwegian furniture manufacturer that commits to long term sustainability, a prerequisite in all parts of their operations, their design of furniture solutions, procurement of materials, and their manufacturing to distribution processes. Using innovative robotic technology, their new manufacturing plant "The Plus" (designed by BIG - Bjarke Ingels Group and scheduled for completion in Autumn 2021), will be carbon zero. The new factory will be the first industrial building in the Nordic region to achieve the highest environmental certification, BREEAM Outstanding, by using solid wood and ensuring a fossil-free and emission-free construction site. The Plus will employ several Industry 4.0 solutions, such as smart robots and self-driving trucks, and the whole factory can be run from a tablet device. Every aspect of the factory will be based on principles of renewable and clean energy to ensure eco-friendly production. The Plus will produce 50% lower greenhouse gas emissions than similar conventional factories.

Additive manufacturing is a straightforward process of making that can impact the production of furniture components from a three-dimensional model adding material layer by layer in filament, liquid, or powder through a digital-driven technological process that can replace or complement traditional fabrication methods. Fields of applications in additive manufacturing, range from prototyping to actual production, and given the widespread use of this tool, an assessment of the environmental dimensions concerning the production phase and the entire life cycle of the components produced is needed (Kellens *et al.*, 2017).

An example of AM utilized in the furniture sector is The Endless Chair by Dirk van der Mooij (2011). It was designed using CAD technologies and digital scripts and manufactured using robotic CAM tools. AM processes are efficient, and waste is minimized. The Endless Chair illustrates the potential in digital CAD / CAM technology to transform the furniture sector.

Fig. 3.3 - The Endless Chair, manufactured utilizing AM technologies. Dirk van der Kooij for Studio Kooij (2011).

High-technological processes are pathways toward achieving sustainability goals and adopting the circular economy model's values. Research suggests that this path can become more circular and needs further study.

3.6.2 Maintain production and components in use over a longer time

The concept of maintaining production of components is critically important in extending the life cycle cost (LCC) of manufactured furniture. Here are a couple of examples demonstrating practices that already extend the life of furniture through the manufacture of modular and standardized components and the accessibility to the components by consumers.

IKEA has a global presence with global markets and distribution aligned with CE principles. Much of their furniture embodies modularity and standardization of components which allows for replacement and repair of its furniture products. IKEA created a material recovery program for home furniture, a take-back campaign for recycling furniture and is pursuing the use of waste from production as a resource for new products which reduces landfills. The company places significant value on democratic design, a concept of making clever design available to everyone. IKEA expands the concept of democratic design into five dimensions, which are: function, form, quality, sustainability, and low price. When there is a balance between all five dimensions, IKEA considers the design "democratic" (*IKEA.com*, 2021).

Re-manufacturing is a feasible alternative to reusing furniture where processes of checking, resurfacing and redeployment apply to the long-life components and assemblies, like steel frames or structural parts. Rype Office, a London-based company, remanufactures brand name office furniture back to as-new condition and creates sustainable furniture from potential waste materials. The result looks and performs as new, but at a significant cost savings, economically and environmentally. Remanufacturing is a strategy that commits to a zero-landfill goal by repurposing old furniture for other uses and/or recycling them into new usable products. Key sustainable factors in the process are eco-sustainability, reducing raw resources, energy, and water, and being in position to sell functioning furniture at a reduced price.

3.6.3 Cycle materials through the production system as many times as possible

The furniture sector is a potential leader for the action of cycling materials through the manufacturing process as many times as possible. Following are examples of how recycling and upcycling can be used to reduce single-use materials.

Fig. 3.4 - Recycled Grey Babila XL by Odo Fioravanti, Pedrali (2020).

Pedrali, an Italian furniture company active in sustainable design, aims to design and manufacture products able to last through time for style and performance. Their collection titled "Recycled Grey" is made of 100% recycled plastic composed of 50% post-consumer and 50% industrial plastic waste. Post-consumer plastic waste comes from products previously used by consumers, such as plastic bottles or food packaging, while the industrial waste comes from industrial processing. The Recycled Grey collection represents a theme already pursued by Pedrali, who has always reinserted in the productive process the byproduct of internal waste of its factories: plastic material scraps, containers, and plastic films. The 50% of post-consumer waste represents the limit that allows this material to guarantee the product's exacting standards regarding durability for the contract sector, their primary activity sector, known for its heavy and prolonged use.

Upcycling describes the process of increasing the value of waste materials through the recycling process, creating a product with a longer lifespan than the original. Lendager UP is a Danish company working in upcycle product development. An agreement between Lendager Group designers, world-renowned flooring manufacturer Dinesen, and Danish kitchen manufacturer Reform results in UP kitchen cabinets which are created from solid wood, post-production cutouts that would otherwise have ended up in the landfill as waste. UP kitchen cabinets are examples of value gained by upcycling.

Fig. 3.5 - Sacco's Green Limited Edition of the iconic chair by Zanotta (2019).

3.6.4 Utilize pure materials to improve the quality of post-life use

Utilizing pure materials can impact the furniture sector by extending the EoL and improving durability and utility of products. These examples identify calculated and conscious decisions to create sustainable furniture options.

Caimi is a leading Italian company in the production of furnishing accessories. Caimi's *Snowsound technology* acoustic panels are composed of 100% recyclable polyester with variable density, which achieve selective absorption at different frequencies to optimize their acoustic performance. Plastic and metal components are easily detachable and recyclable.

Zanotta's remake of the 1969 Sacco has "*gone green*" and is now made of ECONYL®, a regenerated nylon thread made entirely from fishing nets collected from the seabed, scraps of fabric, and industrial plastic. The new material maintains the same qualities and performance as nylon made from petroleum but can be regenerated, recreated, and remodeled indefinitely without using other natural resources. In addition, the padding of the original project, made of high strength expanded polystyrene (EPS) balls, has been replaced with BEWI's BioFoam® microspheres, a biodegradable and compostable bioplastic (PLA) obtained from sugar cane that has the same characteristics of EPS in terms of structure, properties, and technical performance.

3.7 Discussion

The points of action highlighted in the case studies point to concepts and values that matter in the furniture sector. They point to opportunities that the furniture sector can lead with. Across the furniture sector, there appears to be scattered adoption of CE models despite broad knowledge and support for the goals and values of CE models. Why the gap?

Designers, educators, business directors, and the press are all in position to influence consumer perceptions and consumer patterns that can encourage industry to transition away from unnecessary resource depletion, but to do so, attitudes and paradigms must change, and design must demonstrate that it can result in more than superficial changes to products (Andrews, 2015). Change must be systemic on several levels and embrace core aspects in the manufacture of furniture to be consequential.

It was valuable to discover a patchwork of CE criteria adopted by European furniture companies, however, quantitative measure is difficult and complex to obtain. Therefore, it would be desirable to have an agreed upon common set of criteria for the furniture sector, complementary to the Circular Indicators Project developed by the Ellen MacArthur Foundation, and related to the 'Green Furniture Mark' (GFM). Doing so would provide consumers and procurers a simple means of assessing product circularity. Potentially, a GFM could be deployed alongside other existing EU instruments, such as the EU Ecolabel and GPP criteria.

There are many potential benefits to transition and adopt CE models in the furniture sector. Benefits of a higher level of CE in the EU Furniture Sector (EEB, 2017) could result in: 160,000 extra jobs, 3.3-5.7 million tons of additional reused/recycled materials (Improving carbon footprint), and €4.9 billion increase in EU's Gross Value Added (GVA) statistics.

Sustainability and circularity drivers will continue to impact manufacturing processes as well as new business models and new ways of production. This is essential to ensure the European industry's mid and long-term competitiveness with implications for workers and their safety. A circular economy approach in an environmental context could drive innovative strategies to prevent and minimize resource consumption, build into the continual product maintenance of materials in time-based cycles, and recycle potential waste into new uses. In addition to the environmental advantages, the adoption of circular practices results in financial savings.

By developing the knowledge base for greener and smarter manufacturing processes, the authors believe it is possible to achieve a sustainable and more democratic European design culture. Long term sustainable and green designs are embracing smart and innovative CE values involving social, economic, ecological, systems and require a process-based and multi-scale systemic approach to planning and realizing sustainability guided by a target vision (Bagheri and Hjorth, 2007). It is up to us all, designers, industry, institutions, and consumers, to consider sustainable furniture design strategies and consider circular economy models and scenarios in manufacturing when making decisions and placing value in furniture design.

3.8 Conclusions

Our research on CE solutions and strategies has focused on the knowledge gap in the furniture sector. We believe that guidelines and assessment criteria will encourage the adoption of CE models for the manufacturing of furniture in Europe and can help the sector achieve social, economic, and environmental sustainability, and contribute towards reaching the environmental goal of carbon-neutrality outlined in the EU Green Deal. By developing the knowledge base for greener manufacturing processes, it is possible to plan for a sustainable and more socially democratic European furniture design culture.

The furniture industry needs to be encouraged to adopt a systemic transition from a linear economy to a circular economy because it is a more responsible model for achieving the sustainability goals aspired by many European institutional entities. To transition across the industry, designers and companies must adapt to new economic rules of engagement. Additionally, the public sector actors (influencers, media, teachers, customers) need to be further educated about the value of the CE model. With an educated public who expresses interest in C2C products, designers and companies can confidently push the existing boundaries of what is defined as sustainable furniture. But this should not stall any progress each company identifies for itself to be part of a circular economy.

In short, designers and manufacturers need to shift their thinking, by adding [re] into all aspects of making. The takeaway is that there appears to be a gap between the positive attitude towards CE systems and implementation strategies, which suggests potential growth for both institutions and managers involved in sustainable development processes. In this context, there is a clear need to study the impact of legislative and voluntary actions in the next decade, forecasting how a more sustainable CE will affect and transform the EU furniture sector.

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4. Design by data in adaptive morphologies

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Abstract

Design practices have looked at natural systems as the source of inspiration for centuries to emulate their formal aspects and their life and evolutionary complexity. Since the advent of the digital revolution and the technological innovation related to computation, this issue has become increasingly part of the design plan. Today, thanks to the code-based generative tools and processes, design research is increasingly exploring the principles of biology and particularly the aspect of adaptability, which means "adaptive," the ability of an organism to transform its original structure into a different one relating to an environmental condition, and thereby designing a symbiotic relationship between body and surrounding context. As a result, this kinetic and adaptive matrix provides strategies for designing and constructing emerging morphologies and design elements to experience creative possibilities linked to the relationship with the environment.

The chapter proposes a conceptual framework for the topic's exploration in the context of computational design, that is a multidisciplinary area of study which can be defined as the application of computational strategies to the design process and whose relevant aspect concerns the creative, logical nature, and not the mere instrumental component of the "calculation". The essay also aims to encourage rethinking the project's territories, viewed as growingly hybrid context, where boundaries of the design's fields (mainly design, architecture, art, engineering, etc.) can virtuously intertwine with digital subjects of computation and therefore acquiring and increasing design value.

4.1 Introduction

Over the last decade, design has increasingly taken advantage of the growing availability of digital technologies of a computational nature, revisiting and reformulating previously little addressed problems due to their complexity, both in terms of the number of components and the relationships between them. It has led to concepts, techniques, and tools such as algorithmic design, parametric design, generative design, digital manufacturing, and, more recently, design by data. The latter, specifically, comes from representation and generative methodologies and deals with parametric definition and algorithmic processing. Its focus is the use of data from real-time sources, but not only to develop scenarios capable of integrating the variability of the data themselves, both in the dynamics of the simulation as in the adaptive capacity of the physical systems of a built environment. Computer science and new technologies have provided the main paradigms of the subject, while the design has outlined new models and research methodologies.

The reference context for research is the computational design, understood as the design process that, taking advantage of the potential of computation, integrates digital and emerging technologies in the development of a product structured on the interaction between form and information (Reas, 2010). In this framework, the programming and design domains integrate to identify a form of creativity where information becomes procedures and rules of interaction. Furthermore, where data drives a design transition from descriptive to prescriptive approaches establishes an unprecedented feedback loop in design research and production.

4.2 From data to computational design

The architecture has always made use of data in the design process. Specifically, data made of different nature and from various sources, which determined the premises, guided the construction, and reviewed and implemented phases. The quantitative and functional data are those that usually define the beliefs. In contrast, the qualitative data of the relationship with the environment (whether intended as context, people, etc.) structure the articulation, characterizing a specific morphological and spatial interpretation. In the context of this reflection, "set of data" means a collection of "raw" values, not determined to a specific form and scale, which through a process of helpful refinement for their interpretation (a method of translation within a particular domain of reference), become materials through which to build information or structure knowledge. In the case of architecture, this structuring process leads to composition.

The translation of data into representation has thus a double role: i) to build a sort of general framework of the project, which defines the framework of rules and the general principles of interaction; ii) to make the project emerge from an articulated whole, but not yet formed, which already possesses within itself all the elements that will characterize its generation.

Converting data from external domains into a project structure is a problem of rewriting in a different language and equivalence between the parts since the system of signs strictly connects its interpretation within other signs and semantic contexts (Fig. 4.1).

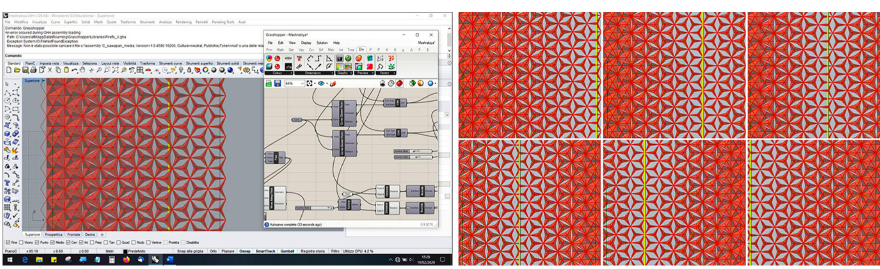

Fig. 4.1 - Simulation of the responsive behavior implemented by facade petals in the Aegis architects' project Al Bahar Tower in Dubai (author's revision of façade detail). The algorithm determines the dynamic morphology of a star origami by calculating the distance of each center from the sun's line of incidence. The transversality of the data is the crucial factor in the design. The data obtained are continuously remapped between 0/1 domain, corresponding to the opening and closing positions of the petals, then used as input in the control of the distance between the points of the geometry.

As Speed & Oberlander (2016) suggest, it is possible to distinguish three main approaches of the relationship between design and data:

i) design *from* data, ii) design *with* data and iii) design *by* data. These three classes, very different from each other, are defined by observing the flow of data. From a condition of substantial static and independence between the two domains (design *vs.* data), progressively changes to another more dynamic and interactive state that interprets the variability of the parameters as a valuable element to explore emerging and non-linear design suggestions.

Specifically, the approach that characterizes the design *from* data relates to those design systems entirely guided by the designer, who then identifies, selects, and draws inspiration from inputs obtained by measuring known elements of the context. And regardless of the methods (observation, interviews, tests, etc.) and tools used in such measurement (analog *vs.* digital). The data is consequently a premise of the project.

On the other hand, in the design *with* data approach, the process is still characterized by designers' determination to guide the implementation of the phases. Still, also it is flanked by data flow from intermediate levels of verification and control of processes/products. This process is not only to collect cold elements of experimental synthesis, useful in the design review but "a condition in which designers should anticipate the disruptive potential that is produced from streams of live data from networked artifacts" (Speed, Oberlander, 2016). In this case, data is played out between the premises and the implementation phases of the project.

With the approach of design *by* data, finally, are collected most of the experiences of the other two classes to project them into a new design dimension and in which systems with large margins of autonomy and not totally defined in their morphologies are governed by other systems, which interact to generate information. Thus emerge: "new products and services can be synthesized via the data-intensive analysis of existing combinations of humans, computers, things, and contexts" (ibid.). The condition of the data is, in this case, dynamic, and the project is structured on open variables.

The design *from* data represents the most classic and traditional approach to the project, in which the linearity of the process is the designer's responsibility. On the other hand, design *with* data is an intermediate phase where this linearity is questioned, and the project opens to interaction with the context. Finally, it is possible to speak of design *by* data when the importance of the data defining the project domain (constraints, requirements, etc.) is significantly marked. Results are therefore derived by developing an algorithm and leveraging new digital technologies and computational science tools. From data, we arrive at the project through the computation (here understood as the algorithm of a parametric function) that defines the behavior and configuration of the space when a set of parameters (geometric, logical, environmental, etc.) changes (Fig. 4.2).

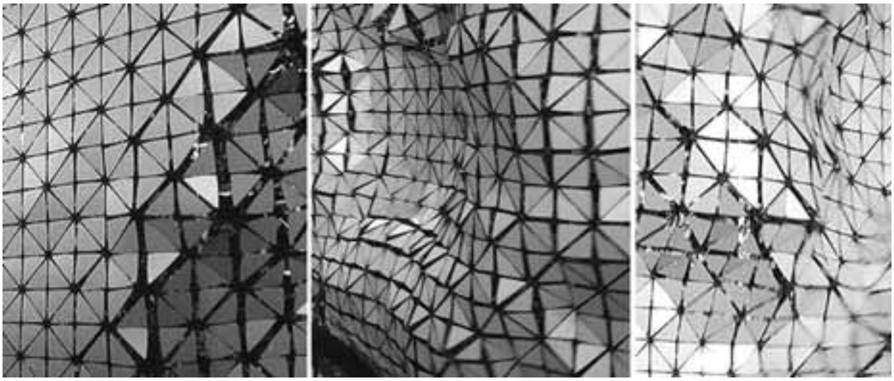

Fig. 4.2 - The Aegis Hyposurface (© dECOi) marked a transition from determined to interactive morphologies. It was a faceted surface able to deform its morphology as a real-time response to environmental inputs: sound, video source, user input, or by pre-configured effects. The surface is made by aluminum facets glued to rubber articulations, able to ensure a fluid visual continuum. A set of pistons drove the facets to generate a dynamic surface as a response to electronic calculation.

Emerging from the same physical space and employing real-time values, these morphologies may continuously reconfigure or adapt to follow environmental and user needs. Variability is what marks their character. This aspect does not relate to the final form of the physical object but to its being an open and indeterminate structure (expressed by the ability to vary along a curve of possibilities), which with this artifact shares the origin of its organization[1].

[1] Bernard Cache (1995) explains a generic design entity with the concept of objective, never completely defined, and more important than its specific elements. The antithesis to the

4.3 From computational design to adaptive morphologies

One of the critical strategies of the computational approach is to "think algorithmically" about the project or to code in the structure of an algorithm, the system of relations that links data to output by processing (Werner, 2015).

With the adoption of the computational approach, the designer does not necessarily leave traditional skills and experiences. Nevertheless, it is necessary to redefine them in terms of objectives, languages, and operating structures; from the mere representation of a single static configuration, the focus shifts to constructing and managing the system of relations that develops the project. Moreover, where the output represents only one of the n-possible interpretations. Thus, the focus of the project task becomes the definition of a design environment separated from the physical representation of its geometry, i.e., a space conceived as a system of relationships, in which the project is the place where a series of parameters generate design iterations.

The gain offered by the definition of the problem in algorithmic terms allows to generalize the problem itself and, therefore, to transfer it to similar contexts, in the way as everyday objects find a diversity of interpretations to the context within which they are inserted, redefining from time to time their skills.

Here is the main difference between classical to algorithmic models: design with algorithms means defining "an architecture of the architecture," and raising the design problem to its generalization finds the abstraction necessary to go beyond a single specificity.

finished object of industrial production follows a specified time, coded use, uniqueness, and invariance of the model to be reproduced. The peculiarity of the objectile is its potential to study an open set of morphologies, where the variety principle (distinctive element to be enhanced and not an imperfection to be eliminated) is more important than homogeneity by options. In order, the concept of objectile Mario Carpo (2011) states that designer's attention shifts from the autopoiesis vision of form to process and numerical matrix at the origin of an open and imperfect object, expression of a function rather than a finite image of geometry and space, able to restores roles and competencies: «new digital platforms for open-ended, interactive collaboration may beget endless design variations, revisions or versions, loss of design control and authorial recognition, and even, in the most extreme cases, collective or anonymous results (...) They may design objects, and then be digital interactors. Or they may design objectiles, and then be digital authors» (Carpo, 2011).

Alongside this, the spread of digital technologies and algorithmic modeling tools extends the ability to simulate and predict the behaviors of design solutions developed in the digital model. The opportunity is mainly due to the enabling possibilities of technologies to interact with the context, leaving potential internal configurations to change in design from an initial condition (Fox, 2013). Data can encode information and become a source to simulate behaviors and shows adaptive outcomes in time: from representation - 2D, or parametric modeling - 3D, design becomes a generative simulation process - 4D (Bier and Knight, 2014). Derived from biology, with "adaptivity," we mean the ability of an organism to modify in whole or in part the elements of its original structure to a different one when specific environmental conditions change.

In architecture, adaptive systems are defined as complex systems that integrate both hardware and software components. The programming (coding of an algorithm) defines the rules of transformation related to environmental inputs. Hence the dynamic behavior is the adaptation of its morphology to the environment to which it refers. As it happens in natural systems, where changes in environmental conditions shape a slow and continuous process of adaptation of their structures, so in the design of adaptive architectures, the adoption of these principles leads to the emergence of artifacts and spatial organizations capable of setting their morphology on the dynamics of action and reaction to a series of external inputs (Fig. 4.3).

At the level of the design process, as well as the skills required to meet this challenge and expected results, there is a "technological horizon that needs a new culture, capable of hybridizing immaterial and material aspects" (Campioli, 2020). These aspects overcome the compositional logic of the whole object and the "solidity" of the building system. Because of the need to respond to specific local conditions, as opposed to generic overall configurations of the composition ordered by geometry, these artifacts are often described as non-standard architecture, and: «employ the building envelope and its articulation and multiplication as a spatial device and environmental modulator» (Hensel and Sørensen, 2014).

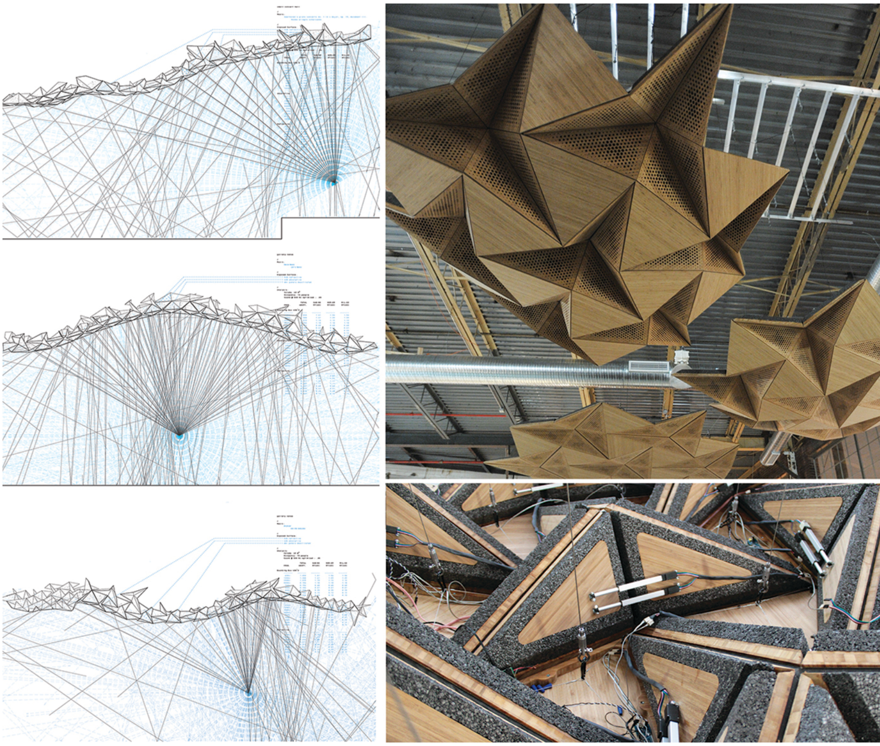

Fig. 4.3 - The Resonant Chamber project (© rvtr) was iterative research and development in computational testing and full-scale prototype installation for the University of Michigan. The project was an exploration of kinetic tessellated architectural systems and variable acoustic surfaces that use specific geometries. The project aimed to develop a sound sphere able to adjust its tessellated origami patterns to achieve the optimal conditions for the sound.

The context outlined by the two authors is hybrid, and the relationship between analog and digital takes on peculiar features. Moreover, where the different disciplinary fields (mainly design, architecture, art, engineering) intertwine with each other and with the topic of digital computation to acquire and increase design value. Boundaries of the various domains and the rigidity of the scale that drive additive compositional logic between the different layers of the construction are blurred (Nebuloni, 2020a). The surface is first discretized into basic modules and then populated by new families of technological artifacts from an organic whole: the adaptive component system.

According to the level at which the relationship between design and data takes shape, these artifacts' adaptive systems are recognized as central and local. The former defines the control of the set of components on the main dimension of the structure (Fig. 4.4). The latter keeps it within the single element that, in this case, will be equipped with sensors, actuators, and microprocessors for data encoding and motion control (Fig. 4.5).

Fig. 4.4 - Soma Studio. Thematic Pavilion for Yeosu Expo 2012 (©Soma). The design's concept for the 140 meters long and 3 to 13 meters height dynamic façade originated from biology and is an example of a central level system. The 108 kinetic lamellas controlled internal light conditions and created organic external animated patterns. Servomotors reduced the distance between the two bearings to originate the movement, resulting in a side rotation of the lamellas.

Fig. 4.5 - Jenny Sabin Studio. Lumen, New York (© Jenny Sabin Studio). Lumen consisted of 250 hanging tubular structures designed to capture and react to changes in sunlight over the day. The concept originated from biology, and its composition refers to a local-level systems typology. The structure's reactive surface was linked to human interaction and environment.

Between the two systems, there are essential differences in the typological structure and data management: in the central systems, the scale of the components is greater, and the control over the whole process, as well as the harmonization between the elements themselves, develops more complex kinetics. In the local systems, the components are smaller and with a form of intelligence that allows them to produce individually simple movements and achieve complex and unexpected overall results.

The analogy is to the difference that occurs in nature between the plant systems - with a disseminated intelligence and largely autonomous -, and animal systems - where the control is at the central level. In the first system emerges a logical relationship between homogeneous parts, while in the second, a structure of superordinate elements and succession between them.

Therefore, the characteristic of adaptive architectures is an aesthetics of movement resulting from the ability of action of a plurality of dynamic artifacts like each other. The form - or rather the configuration, potential and induced by data - is a function of the parameters' degree, and a program (algorithm + coding) governs the behavior of the system: the algorithm founds the logic, while the code implements it in a formal language (Nebuloni, 2020b).

Most modeling software integrates interfaces or plug-ins (apps that add advanced functionality to the essential software) to explore these morphologies in the project. With proper programming languages, these interfaces allow the customization of the modeling environment, the definition of algorithms, and control data. In these environments, the algorithm often uses visual programming paradigm, mainly through block and flow diagrams.

These skills also enable interoperability between different digital design environments and platforms, which is essential for integrating external inputs into the process.

The result is the communication and interaction between different domains (e.g., Grasshopper and Firefly plug-ins) that connecting in a bidirectional way an algorithmic design environment to a microcontroller (e.g., Arduino). Data from sensors are, therefore, processes to simulate the physical behavior of a component. Virtual environment and a real physical one are both engaged (Fig. 4.6).

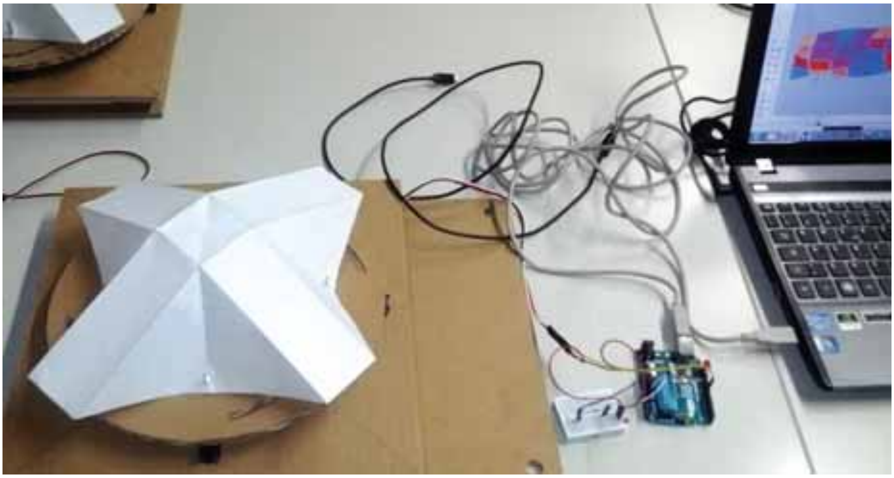

Fig. 4.6 - Digital-physical interaction via a prototype. Simulation of the responsive behavior of a design component (Responsive morphologies Workshop, Polimi).

4.4 Conclusions

Over the past few decades, digital technology has already contributed significantly to the redefinition of design practice.[2] Today, the greater diffusion of tools, techniques, and languages capable of integrating programming into modeling and the possibility for the designer to build custom working tools foreshadow even more important changes. Among them, in addition to the ability to analyze a plurality of data and information proper to computation, the role of enabling technologies in connecting environments and simultaneously

[2] There are three design research stages in the recent history of the digital revolution in architecture (Wiscombe, 2015): the first decade of openness (the nineties), characterized by the free and seemingly unconstrained forms brought by new tools and techniques, from which a figurative apparatus made of hybrid and not rigidly defined morphologies, far from the references of history and no longer articulated on the composition of the parts, but based on the processes of generation linked to the matter, has derived; the second (first decade of the two-thousands), markedly computational, of experimentation on the forms of programming and modeling algorithms, in a game of scale between the variability of a single element and the projection of the same on the morphology of the whole; the current (from 2010), which reinforce the loyalty to the relational aspects of the project focuses on adaptive objects and the dynamic logic of algorithms.

managing many design options. New references, resulting from the changing relationships between environment, construction, and design, are followed by the definition of new interpretative frameworks focused on the behavior of systems and the ability to connect contents and exchange information. Combining and harmonizing the skills necessary for effective and creative use of digital technologies is increasingly needed to explore the potential of the relationship between design and data, implying that designers "reset" the classic tools of the project to build new languages based on variation and complexity.

There are still many risks and obstacles that characterize this hybrid and creative phase of the digital project to make definitive statements about its viability. Above all, the relation to cultural references and examples that, although promising, identify architecture as a mere space of representation of concepts far from its disciplinary domain. Therefore, it will be essential to broaden the discussion to include: "beyond ontology and epistemology, the key issues of function, typology, and technology" (Wiscombe, 2015). Not least, to combine performance aspects with an aesthetics of movement leading to a definition of form that is increasingly dependent on dynamic environmental variables.

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5. Developing Interactive Architecture Prototypes by Means of Design-to-Robotic-Operation

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Abstract

Concepts for Interactive Architecture have been developed since the 1970s and more recently with advancements in Cyber-physical Systems and the Internet of Things these concepts have increasingly been developed towards practical applications. This chapter presents Interactive Architecture applications developed at Technical University Delft using Design-to-Robotic-Operation methods. They are proof of concept for the potential of interactive systems to seemingly disrupt the linearity of time and improve spatial experience.

5.1 Introduction

In the 70s (inter al. Eastman, 1972; Negroponte, 1975) speculation on opportunities introduced by the digital technologies initiated a discourse on intelligent environments in architecture. Since then, various applications have been developed for Ambient Intelligence (AmI) (Zelkha *et al.*, 1998), Interactive Architecture (inter al. Fox & Kemp, 2009), Adaptive Environments (Bier, 2018), etc.

In the same line of experimentation, the Design-to-Robotic-Production- Assembly and -Operation (D2RPA&O) framework developed in the Robotic Building (RB) lab at Technical University Delft (TU Delft), explores the potential of robotic and cloud-computing technologies and their integration into buildings and building processes (Bier *et al.*, 2018). D2RPA&O makes use of Cyber-physical Systems (CpS) and the Internet of Things (IoT) in order to monitor physical processes by creating virtual representations of the physical world that support decentralized decisions making (Rajkumar *et al.*, 2010). Thus, D2RPA&O relies on (a) interoperability, which is the ability of robotic systems, humans, and buildings to connect and communicate via the IoT, (b) virtual-physical coupling by linking sensor-actuator data (from monitoring physical processes) with virtual models and simulations, (c) decentralization, which exploits the ability of cyber-physical components to operate autonomously, and (d) real-time operation implying that data is exchanged in real-time.

Several case studies focusing on D2RO as part of the larger D2RPA&O framework will be presented. Their aim is to extend human capabilities and experiences in the built environment by means of sensor-actuators. Even if different from D2RP&A, D2RO is seen in terms of the processes involved as very much similar because they all involve some level of automation and Human-Robot Interaction (HRI). Similarities and differences will be identified in the sections 'Case studies' and 'Implementation' with the section 'Conclusions' framing achievements so far and identifying future steps.

5.2 Case studies

Several case studies are presented in which virtual and physical worlds communicate with each other:

5.2.1 Interactive Façade (2019)

The first case study has been implemented as workshop at TU Delft with the goal to develop a façade that responds to human and environmental needs. While people's movement and posture was recognized using Kinect, an array of sensors provided ambient lighting data. This data combined with weather data throughout the day provided the basis for predictive analytics. Multiple Arduinos were distributed along the façade and work as an intelligent swarm to implement reconfiguration of the façade according to sun conditions and users' movement

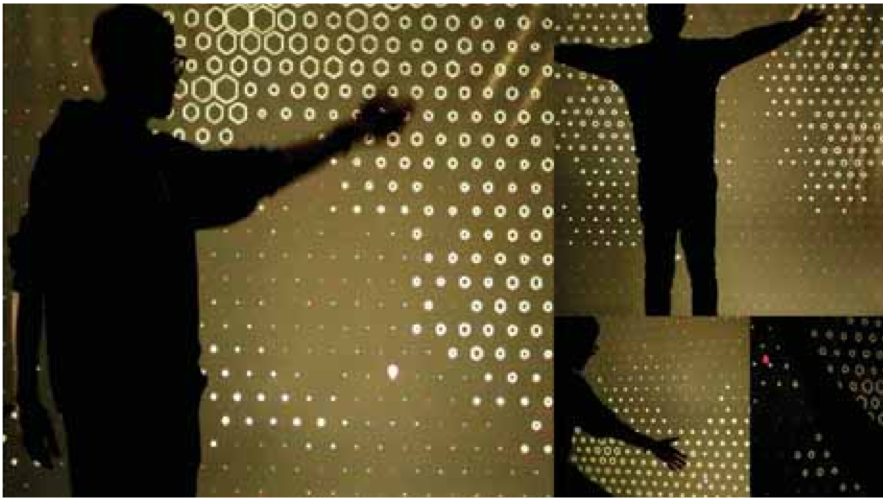

Fig. 5.1 - Façade is responding to user's movement and environmental conditions.

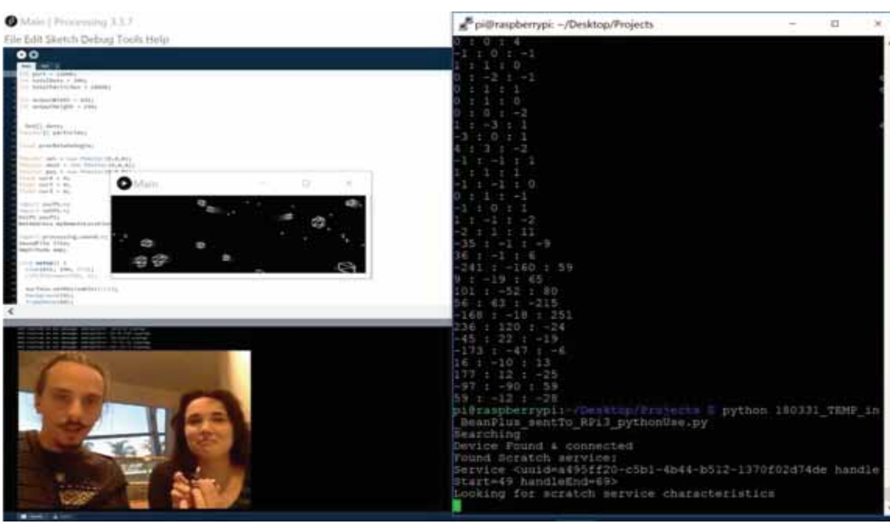

Fig. 5.2 - Linking accelerometer with virtual representation.

in space. When linked to Artificial Intelligence (AI) in order to able to learn from the data accumulated in time, the system improves and proactively proposes reconfiguration of the façade by increasing or decreasing shading, transparency, etc. It not only connects the virtual and physical environment in a functional but also a playful way, which has been the focus of the next case study (Fig. 5.2).

5.2.2 Hiperorganicos (2018)

Organised by Núcleo de Arte e Novos Organismos (NANO), Federal University of Rio de Janeiro as part of the Hiperorganicos symposium (2018)[1] the workshop offered by TU Delft focused on the development of sensor-actuator prototypes linking virtual and physical worlds. Participants developed various prototypes from which one is showcasing a ball on strings linking its physical movement in space to its virtual representation thus creating a virtual-physical continuum (Fig. 5.3).

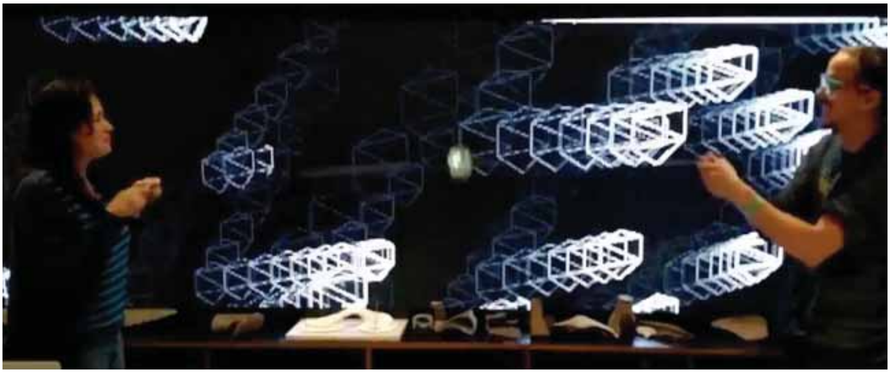

Fig. 5.3 - Accelerometer embedded in ball on two strings is used link the physical movement with its virtual representation.

[1] https://nano.eba.ufrj.br/hiper8/.

Using sensor-actuators and processing[2] the physical ball is linked with the virtual. Each movement of the ball initiates transformations in the virtual world. The virtual and physical worlds mirror each other in a playful way. While there is only one physical ball moving in a controlled trajectory of up and down, the virtual world represent multiple balls showcasing the artistic interpretation of the trajectory.

By introducing Design-to-Robotic-Operation (D2RO) framework developed at TU Delft workshop participants design explored the use of Wireless Sensor and Actuator Networks (WSAN). Projects aimed to interface the virtual and physical worlds via intuitive mechanisms, where physical actions mirror actions or reactions in the virtual environment. The project presented here used physical motion to define the position of digital objects within a virtual space (Figs. 5.2 and 5.3). In this project, a wearable device integrated into a ball on two strings was used to link accelerometer data wirelessly to a virtual environment. This data informed the virtual environment to mirror the physical movement within the physical space. By connecting the physical with the virtual, the architectural space transforms into a hybrid environment, wherein spatial experience is not anymore sequential.

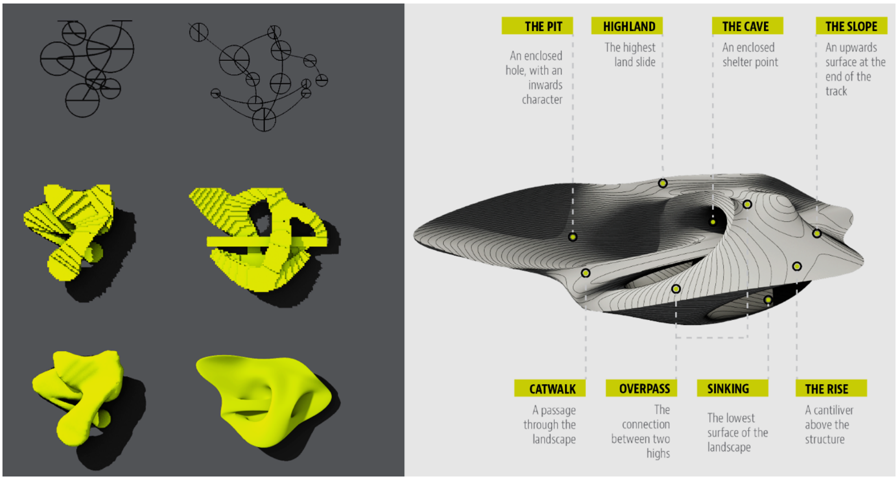

Fig. 5.4 - Landscape-like design based on activities 24/7.

[2] https://processing.org.

5.2.3 Interactive Urban Furniture (2017)

The third case study explores the potential of interactive systems for urban furniture[3] with movement sensors and lighting actuators integrated into a landscape-like design located at the river side in Rotterdam. The study of activities and potential new activities on respective location played an important role in the design (Fig. 5.4). In addition, factors such as climate, water tides, surrounding urban context, flora and fauna, etc. were studied. Once the parameters to inform the design were identified, the form-finding process was initiated using activity patterns as driving force. Voxels were employed to define the scale and distribution of activities in each part of the urban furniture and then their smoothening was implemented in order to achieve a continuous easily accessible landscape.

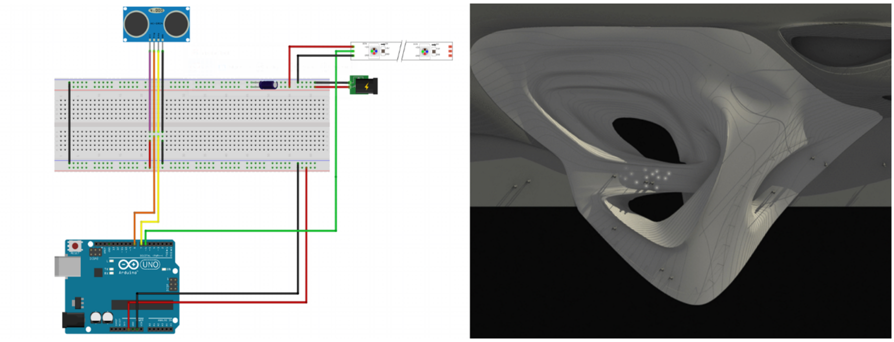

Fig. 5.5 - Sensor-actuators integrated in the urban furniture.

The integration of sensor-actuators was implemented in relationship to the identified and newly defined activity patterns. Lights were integrated to not only assist users with their activities but also instigate playful interaction in form of ‘catch me if you can’ or similar. The lights would turn on and off, change intensity or color depending on the activities that are taking place and the time of the day. They would precede or follow runners or surround resting users.

[3] http://uf.roboticbuilding.eu/index.php/Msc1G3:Group.

When enhanced with AI, the system is envisioned to be able to learn in time based on users' behavior. The system may start with a basic set-up that improves in time based on collected data (Cheng *et al.*, 2017). The system may become in time more attune with local conditions and users' needs. Users may give as well direct input via an app so that the system is able to recognize specific users and adapt to their individual needs, perhaps, even initiate alternative interactions that users could appreciate.

In this context, the space becomes an active participant in the spatial experience of the user, disrupting the linear experience of space and time in architecture. Spatial experience changes in time while users move through space. By integrating robotic, AI, and IoT applications into architecture, the design, production and operation of physically built environments establish an unprecedented feedback loop, which has been further explored in a project with focus on Ambient Intelligence (AmI).

5.2.4 Interactive Podium (2016)

An extended AmI enabled by a Cyber-Physical System (CPS) built on a Wireless Sensor and Actuator Network (WSAN) has been developed (inter al. Liu Cheng *et al.*, 2017; Bier, 2018) by integrating amongst others, Human Activity Recognition (HAR), in order to regulate interactively inter al. illumination (Fig. 5.6). Integrated in a podium with LED-lights the system responds to three states: (1) Initiation, (2) Lecture, and (3) Break. In the first state, the lights start to pulsate indicating that the podium goes through a starts up procedure. In the second state, the lights react to the speaker, by change color and intensity. In the third state, the lights respond to the audience and their movement during the break. The system is equipped with Machine Learning (ML) algorithms in order to identify which combinations of light color and intensity contribute to the comfort of the speaker. Hence, the system aims to improve the state of the speaker by regulating the light via ML mechanisms using HAR (Liu Cheng *et al.*, 2017).

Fig. 5.6 - Interactive stage at the Game Set Match symposium 2016.

5.2.5 Drones Swarm

Moving beyond integration of interactive devices into the built environment, in a project developed for a fictive world expo, students designed swarms of drones that guide visitors through the exhibit site and create temporary dome-shaped pavilions (Fig. 5.7). The swarm of drones was conceptually designed to operate semi-autonomously. The drones rely on Swarm Intelligence (SI) to act as a coordinated swarm. They follow simple rules of separation, alignment and cohesion and are communicating with each other while being as well aware of the environment hence avoiding collisions and aggregating in specific configurations.

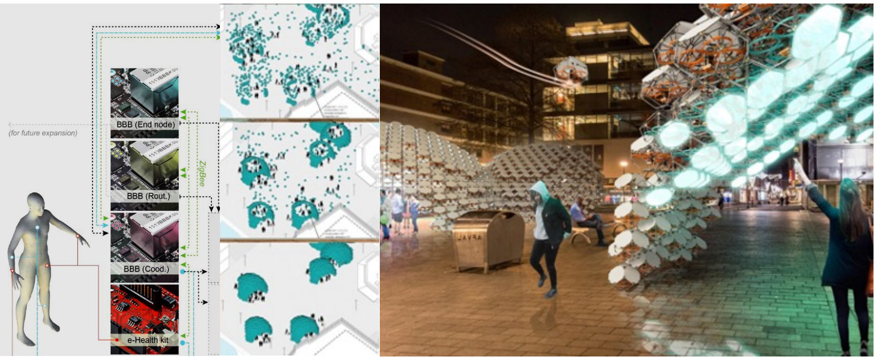

Fig. 5.7 - Swarms of drones reconfiguring according to human needs rely on a bio-cyber-physical feedback loop.

In this context, developing ML models in order to introduce capabilities of learning in time, is a challenge. If SI works with data collected within a short period of time, ML employs data collected from users and environment over a longer period of time with the aim to learn to respond to users' needs by establishing a bio-cyber-physical feedback loop (Fig. 5.7). Such feedback is required mainly because Cyber-physical Systems (CPS) are designed to be autonomous but present uncertainties with respect to complex decision-making, troubleshooting, etc. (Pillan *et al.*, 2020). The Bio-CPS model is integrating computational and physical elements with biological systems (Fass and Gechter, 2015). Such an approach ensures that the built environment actively responds to human needs. The responsive environment is sustainable because it learns from users and its functionalities are attune with what is needed (Liu Cheng *et al.*, 2016). As a result space is more comfortable, use is more efficient, and energy loses are reduced.

Such ML algorithms employ data collected from users to learn how to respond to users' needs by establishing a bio-cyber-physical feedback. The design of such feedbacks requires D2RPA&O methods (Bier *et al.*, 2018) that learn from users and the environment. This learning process takes place in both the D2RP&A as well as in the D2RO processes. While D2RO links the design to the operation of buildings, D2RP&A focuses on linking the design to the production and assembly process of buildings (Fig. 5.8). Together, they establish a comprehensive framework for AI supported building of buildings that are imbued with AI. Both, AI embedded in building processes (based on D2RP&A) and AI embedded in buildings (based on D2RO) involve on some level Human Robot Interaction (HRI). If in D2RP&A processes, humans work safely together with production robots, in D2RO humans interact safely, healthily, and pleasurably with the robotic built environment. In both cases the new meaning of building production and operation is not created by the one or the other, but by the interaction between the two.

Fig. 5.8 - Human assisted robotic assembly by stacking.

So far AI has been integrated mainly in D2RO (inter al. Liu Cheng, 2017; Bier *et al.*, 2018) and more recently the integration into the D2RA process has started (Fig. 5.9) with the robotic arm using ML, and computer vision techniques, such as OpenCV, to find location of nodes, detect the related linear elements, pick them with a gripper and transfer them to the intended location (in the next proximity of the node) one by one, while considering obstacle avoidance (human safety). In this scenario, the human will navigate the arm with his/her hand, and in order to move it to its final location (the node). For that the following steps are considered: (a) Localization by creating a map of the environment (including nodes, linear elements, and human location); (b) Robot's location by object detections (using OpenCV to detect the correct node, and do the corresponding action); (c) Controlling and navigating the gripping toward the objects in order to pick up the objects; (d) Human action involving controlling the gripper manually to insert the linear element in the node.

The overall goal is to let the tasks that are more easily implemented by humans in human control while the others are taken over by robots. The question of what tasks are automated or semi-automated in D2RA has been first formulated in a human-assisted robotic assembly exercise that involved staking.

Fig. 5.9 - Computer vision approach (right) developed for human-robot collaborative assembly of linear elements and node (left).

5.3 Human-assisted robotic stacking

The project focused on human assisted robotic assembly involving stacking linear elements with varied sizes in multiple directions (Fig. 5.8). Several processes of parametrization, structural analysis, and robotic assembly were algorithmically integrated into the D2RP&A method. This method was informed by the systematic control of density, dimensionality, and directionality of the elements. As all other processes, it was tested by building a one-to-one prototype, involving development and implementation of computational design workflow coupled with robotic kinematic simulation that is enabling the materialization of a multidirectional and multidimensional assembly system.

The virtual and the physical processes were linked in all phases from design to production and assembly, while humans and robots worked side-by-side requiring consideration for HRC, which is now being developed.

5.4 Implementation

These case studies were developed as combined research and education projects taking advantage of synergy effects between researchers, PhD and MSc students, who were gradually familiarized with the use of computation and robotics embedded into buildings and building processes.

D2RPA&O builds up on interaction between human and non-human agents not only at design and production level but also at building operation level, wherein users and environmental conditions contribute to the emergence of multiple architectural configurations (inter al. Bier, 2018). These utilize sensor-actuator mechanisms that enable building components and buildings to interact with their users and surroundings in real-time. Their conceptualization and materialization process requires D2RPA&O chains that link design to production, assembly and operation of buildings. In this context, design becomes process-oriented and use of space is time-based, which implies that architects design increasingly processes from which sensorially or/ and physically reconfigurable buildings emerge.

As presented in the case studies, reconfiguration serves a variety of purposes and requires advanced virtual modeling and simulation that interface the production and real-time operation of physically built space through D2RPA&O.

As earlier indicated, the virtual and the physical processes are linked and need to take into account the inherent multifaceted nature of building from the early design to the latest building operation phase. Challenges in terms of scale, multi-tool and multi-robot production and operation need to be examined in order to achieve chained processes by linking virtual models (such as Rhino 3D model with Grasshopper plug-ins such as Millipede, Ladybug, etc. for simulating structural and environmental performance) with robotic devices. The aim is to develop/ implement chained D2RP&O processes in which robots take specific roles while all (human and non-human) members of the setup including respective (virtual and physical) systems receive feedback at all times (inter al. Nazzari and Bier, 2020).

D2RPA&O has been so far developed with the vision in mind that building processes and buildings will be increasingly incorporating robotic systems supported by AI. The question for the future is thus not if but how D2RPA&O will improve building processes and buildings while addressing societal challenges such as scarcity, overpopulation, climate change, etc. So far D2RPA&O has proven to improve material, energy, production and operation efficiency. Mid- and long-term automation of tasks and processes that can be automated will be implemented in a similar way as the car industry has automated its tasks and processes. Then HRI and ML will be increasingly incorporated in processes. The human remains involved in tasks that are requiring subjective assessment or high-level strategic planning.

In this context, architecture and building construction fundamentally change as buildings and building processes become parts not only of an urban network but also of a larger Internet of Things (IoT) which enables not only production steps but entire value chains to be optimized, whereby all phases of the life cycle from idea to development, production, use and maintenance up to recycling are considered. This ensures the development of sustainable approaches that address today's societal challenges and improve daily life.

5.5 Conclusions

Presented projects identified opportunities to engage in the integration of CpS in architecture, while promoting visions of not only functional but also playful interaction. Such interactions seemingly disrupt the linear reading of time when deployed in the mixed-reality built-environment. They rely on today's virtual-physical continuum and are indicative of tomorrow's interactive environments, wherein humans interact with CpS that are endowed with increasingly higher levels of intelligence.

While D2RP&A and D2RO are fundamentally different, since the one focusses on building production and the other on building operation, they are similar in the way the tasks required in the production and operation processes are automated. Considering that about 50% of all tasks can and will be automated, while 45% will rely on HRI and 5% will remain in human hands[4], the question of impact on architecture and society at large needs to be addressed. Automation is offering solutions that make the design, production, assembly and operation of buildings more efficient. At the same time, automation rises questions

[4] https://www.mckinsey.com/featured-insights/digital-disruption/harnessing-automation-for-a-future-that-works/de-DE

related inter al. to the use of personal data, the social impact from expected labor skill shift due to increased automation and the challenge to respond to the demand of developing new skills (Pillan *et al.*, 2020).

Considering the expected labor skill shift, the question is how academic education responds to the challenges of automation and the subsequent requirement that architects develop new skills. Contrary to the preconception that robotization is not architecture related in its essence, the challenge is to understand the same way the modernist architects understood that the industrial revolution 2.0 changed architecture, that industrial revolution 3.0 and 4.0 with their robotic, AI, IoT applications have a major impact on architecture transforming not only its design and production but also its operation towards becoming a cyber-physically enhanced (production and operation) system (Bier, Chan, Cervone and Makaya, 2021).

Acknowledgements

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6. From smart materials to Animate Objects. Reframing smartness through behavior exploration

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Abstract

Today, a new class of materials and objects are entering our daily lives, giving interest in smart devices research and robotics in our societies. As a result, we are experiencing a renewed interest in "material agency" and the reconfiguration of our environment through the hybridization of physical matter and digital performance.

The purpose of this paper is to highlight the research direction of MADEC - the Material Design Culture Research Center in the Design Department of the Polytechnic University of Milan - on the *phygital* evolution of product design and the design implications of *animate objects*, which we will define. Since technology has allowed the transition from graphic interfaces to shape-shifting ones, designers are experiencing new challenges. We frame the topic of smart evolution of objects through the existing literature, and investigate issues like their new features, behaviors, and aesthetic implications. Then we analyze a few case studies to stress the fundamental aspects to consider when approaching the design of animate objects.

We believe it is time to strengthen design-led research on behavior of animate objects. Their qualities cannot be detached from design aspects inherent to their tangibility during interaction, such as form in time and expressiveness. These aspects shape users' behaviors in terms of new functions as well as cultural, social, and ethical dimensions that are at the basis of collective meanings and values.

6.1 The new *phygital* materiality

Materials, one of the fundamental elements of design culture (Manzini, 1986; Raimondo, 2006; Ferrara, 2017), have today acquired new importance in qualifying the intelligence of artifacts.

Recent advancements in the materials field - rapid manufacturing, electronics miniaturization, computational tools, programmable matter, modular micro-robots, and integration - are introducing new design variables, enabling researchers not only to apply advanced materials but also to conceptualize, program, develop, and then use new smart material systems.

Conventional materials (fabric, plastic films, leather, wood, etc.) tightly integrated with interactive technologies (sensors and actuators; connection modules; inexpensive, small microprocessors, etc.) have given birth to, what we define as, a new *phygital materiality* (phygital comes from physical + digital), which in a previous study we named "ICS-Materiality", where ICS stands for interactive, connected, and smart (Ferrara *et al.*, 2018).

Mainly applied in robotics, smart material systems affect the design of new artifacts thanks to their abilities to sense, actuate, and perform local computing, as well as their communicating elements (McEvoy and Correll, 2015). Moreover, these materials have been shown to have a certain intelligence and autonomy, as well as a special formal performance, i.e., the ability to change shape and appearance and thereby impact applied research, generating "Shape-changing Material Interfaces" (Coelho and Zigelbaum, 2011). This ability generates an effect that, if it not the same it is at least comparable whit what in context of the performance art, dance and theater has been defined "digital performance" (Dixon, 2007, p. 3), i.e. a performance where technology «play a key role […] in content, techniques, aesthetics, or delivery forms».

The phygital materiality with its behaviors, i.e., its diverse forms in temporal and spatial structures, has a fundamental role in "material agency"[1] (Van Oyen, 2018) as an active player in the interactive

[1] The concept of agency is vital to understanding the productive nature of material-discursive practices, including technoscientific ones.

process. Agency is not a property of each user, and neither is it a pre-given property of an artifact or material. It doesn't merely depend on material and sensorial qualities either; rather, agency is an emergent relationship from the unfolding of transactions between humans and object materiality (Tholander *et al.*, 2012), for instance in the case of "Ultra-Surfaces" developed by a MADEC team (Ferrara and Pasetti, 2020). Ultra-Surfaces ability to perform dynamic behaviors while interacting depends on their phygital materiality, applied in specific configurations. It appears that they have a form of agency that allows them to achieve a certain goal while developing closer relationships with users. The user's actions and the object's materiality together contribute to a unique relational experience.

We consider this particularly important for what we will examine in depth later: the behavioral and animacy aspects of *animate objects*.

6.2 The discourse on objects' smartness

Since computing and the digital revolution entered everyday life in the late 80s, concepts such as "ubiquitous computing" (Weiser, 1993), "internet of things" (Ashton, 2009), and SPIMES (Sterling, 2005) have stimulated reflection on scenarios about features of spaces and artifacts. Recently, Mike Kuvniasky (2010) has talked about "smart things", things that are embedded with smartness or intelligence, identification, automation, monitoring, and controlling functions.

In the industrial design community, the issue of objects' evolution has been faced by the scholars Ezio Manzini (1990) and Giovanni Anceschi (1993), who added to the literature on "Ambient Intelligence" (Aarts and Marzano, 2003).

While Manzini developed a theoretical reflection on "cognitive artifacts" (1990), Anceschi (1993) developed a reflection on interfaces. For Manzini and Anceschi, the fundamental transformation affecting design is the entry of the fourth dimension: time. According to Manzini (1990), to design the interactivity means

> dare al tempo il valore di parametro organizzatore [...] occuparsi dell'interattività significa dunque avventurarsi su un territorio del tutto nuovo, i cui riferimenti

culturali vengono [...] dal cinema, dal teatro, dalla musica: da attività, cioè, in cui la qualità si produce organizzando sequenze di eventi (Manzini, 1990, p.140).[2]

Together with time, Manzini identifies another relevant characteristic: «il modo in cui gli attori coinvolti nella generazione dell'evento collaborano per raggiungere il risultato previsto»[3]. This vision seems to us to successfully frame the concept of agency as an emergent relationship from transactions between humans and objects.
The Ambient Intelligence vision emphasized the qualitative features of sensitive, responsive, intelligent scenarios in order to support the design of user-friendly and unobtrusive artifacts for humans in their everyday lives, offering at the same time a more fulfilling user experience. Similarly, the literature on "Calm Technology" (Weiser and Brown, 1997) has contribute to spread an approach to humanly fit technology.

In the late 80s, the HCI and Interaction designers community began to address interactivity by focusing firstly on technical aspects and then on usability. Recently, several authors have shifted their focus toward an "aesthetics turn". The contribution of Donald Norman (2002)[4] is one of the most incisive in overcoming the paradigm of efficiency and functionality by including reflections on usability and also emotions, feelings, relationships, and psychological and semiotic aspects of objects and their behaviors, all as elements that improve usability.

The current "material turn" in interaction (Robles and Wiberg, 2010), related to material interfaces, has accelerated a return to basic design (Hallnäs, 2011) as well as a move toward "pragmatic aesthetics". The latter allows researchers to focus on the aesthetics of behaviors, the finality of design, and new artifacts (Russo and Ferrara,

[2] Translation: «giving time the value of organizing parameter [...] dealing with interactivity means therefore venturing into an entirely new territory, whose cultural references come [...] from cinema, theater, music: from activities, that is, where quality is produced by organizing sequences of events».
[3] Translation: «the way in which the actors involved in the generation of the event collaborate to reach the expected result».
[4] Norman states «attractive things make people feel good, which in turn makes them think more creatively. How does that make something easier to use? Simple, by making it easier for people to find solutions to the problems they encounter».

2017). In this scenario, we think it is time to strengthen design-led research on phygital design, because the quality of any object cannot disregard those design aspects inherent to their materiality, nor the cultural, social, and ethical dimensions that are at the basis of objects' meanings and values.

6.3 Animate objects: an attempt at definition

Coming from the Italian Design Culture that has developed in a strict interplay between humanities and technology, we choose to adopt the term *animate objects* for those emerging intelligent everyday objects that are able to perform behaviors thanks to their phygital materiality.

The adjective *animate* was first used by Anceschi in his previously cited book to describe the fundamental novelty of "colloquial objects" (p. 9), i.e. objects' «new ability to interact with us»[5] (Anceschi, 1993). Highlighting the phenomenon of new technical objects' status and abilities, Anceschi adopted a bio-constructive perspective, the same applied to the development of artificial intelligence with reference to the intelligence of nature. In line with this perspective, we also use the term "animate", which derives from the Latin *animat* and indicates something «alive or having a life»[6]. Already, in a previous study, we used the expression "almost-living objects" to define the same category of everyday objects implemented with emerging technologies. These are «capable to somehow interact with human beings, determining interesting connections and emotional responses in terms of what can be defined as a sub-branch of the applied aesthetics domain, smart aesthetics» (Russo and Ferrara, 2017).

With their "behavior", animate objects modify the relational space, modulating their connection by following users or other objects.

Through analyses of case studies, including those that we will present later on, we have identified and characterized animate objects

[5] Anceschi derived this term from anthropologist Franco La Cecla's (1991) neo-animist theory of objects.
[6] From the Oxford dictionary.

according to their main features. This allows us to highlight which aspects we believe must be taken into consideration when approaching their design.

- **Shapeshifting**
  This is the capability to change state and appearance thanks to phygital materiality. The activation of light signals, sounds, colors, temperature, movements, and even smells are changes that show the capability to respond to stimuli and interact.
- **Data processing**
  This is the capability related to the Internet and computational processes. Animate objects can, through the Internet, collect, process, and exchange data and information, affecting objects', and consequently users', behaviors.
- **Independence and pro-activity**
  A certain degree of independence and pro-activity contributes to animation. This is critical to shifting from a purely functionalist and passive view of objects' performing a specific function toward an active behavioral function view.

These capabilities contribute to objects' shaping, expressing, and performing behaviors, and stimulating responses to users or other objects which in turn can further influence users and stimulate new behaviors. These are the fundamentals for a smart experience and aesthetics.

6.4 The role of aesthetics in the design of animate objects

According to the designer Yves Béhar:

> aesthetics is the support of experience both from the appearance and the functional side of an object, driving one's eyes or hands toward the product so as to strengthen the temporal and structural logic of the project (Béhar, 2020, p. 234).

In the last decade, the scholar Lars Hallnäs (2011) has launched a proposal for a revision of the aesthetics of interaction at a fundamental level. He suggests taking a step back from the perspectives of experiential design and design for emotion, and to revisit the elementary notions of form and expression based on design fundamentals (form, color, texture, sound, smell, and behavior), rather than focusing on behavioral and social sciences as is common in HCI. He relies on an approach that focuses on the “act of use”, “interface”, and «processes of learning how to use given things», with strong relation «function and interaction in space and in time». He defines the central design dimensions for the classification of interaction design variables as the following:

- Timing - the rhythm and meter of use we introduce.
- Spacing - the space of use we introduce.
- Connectivity - the connections of use we introduce.
- Methodology - the ways of use we introduce (Hallnäs, 2011).

Other scholars maintain a double focus on expression and experience, meaning the aesthetics of interaction remains somewhat different from the aesthetics of traditional product design (Petersen *et al.*, 2008). Thus, despite the abundance of studies, HCI has not yet been able to achieve a clear and convincing aesthetic perspective.

We believe that today it is essential to recover a basic design approach. We also believe that it is important to articulate a perspective capable of incorporating contributions from other disciplines to structure design purposes in terms of method and ethics.

Currently, one of the most respected perspectives on aesthetics is Richard Shusterman’s pragmatism. Briefly, an “aesthetic experience” has a practical use as well as an intrinsic value. It «invigorates and vitalizes us and thus helps us achieve the ends we pursue» (Shusterman, 2000). It relates to a user’s experiences and is linked to the socio-cultural context because the meanings and values we attribute to objects constantly change as cultural groups change. It has an ethical and social dimension.

Form, which is “a dynamic interaction of elements” (Shusterman, 2008), is closely related to the aesthetic experience and is strongly linked to the body (its senses and movement) and the social conditions that helped structure it. Finally, Shusterman’s “somaesthetics”[7] puts the body and its movements back at the center as fundamental parts of feeling and thinking (Shusterman, 2011). The human participates and structures the aesthetic experience with his body and mind.

[7] Somaesthetics combines the terms “soma” and “aesthetics”.

These concepts are particularly relevant for the design of animate objects because they reveal the wide potential for interacting with them. Their shapeshifting in time makes them agents of "kinesthetic interaction" (Fogtmann *et al*., 2008), including multisensory stimulation and excitement, movability, implicit and explicit motivation, and empathic response related to the body. Emotional, affective, social, and cultural stimuli are added to the body stimulation process, leading to cognition, reasoning, and judgment.

6.5 The behavior of animate objects

In neuropsychology, behaviors are the externalizations of emotional processes, associated with bodily movement and certain orchestrations of reactions to given causes, within a given environment (Damasio, 2000). Regarding objects, behavior is related to action and reaction, to what happens in a particular context, and to a change of state or a movement in time that occurs in the object itself. We refer to behavior as an orchestration of dynamic sequences of physical movements or a change of state in the material world (in form, color, light, density, sound, etc.), making an explicit link between form and expression, the abilities to stimulate relationships with users and create specific experiences.

In biology, a behavior is a neural response that results in a stimulation of the senses and an effect on motor activity.

We can then define the behavior of an animate object as the production of transformations that we can observe and promote or that are implemented in response to an environmental change - but always self-generated toward a specific goal or as a reaction to an external event.

Animate objects are sources of change through their behavior according to a principle of intentionality, i.e., a design.

On the behavior of objects, there is also the recent literature on "behavioral objects" that connects art, robotics, and cognitive psychology to emphasize a double point of view: the agency of behavioral objects and the cognitive faculties of the observer (Bianchini *et al*., 2016; Levillain and Zimbetti, 2017). Firstly, this focus recalls anthropomorphism, i. e. the innate tendency to readily attribute formal and mental states (emotional, intentional, behavioral, etc.) to living and nonliving entities. Animate objects, having the ability to interact with the external world, suggest living-being-like (anthropomorphic, zoomorphic, or even plant-like) traits to an observer, as well as mental traits. When this happens, the relation of the user with the non-living entity manifests an affective state.

We believe that the behavioral characteristics of animate objects must be studied and designed in the light of physical variables that relate to changes of state (form, dimension, density, light and color effects, movement, etc.). There are already some guiding principles around this, for instance regarding movement.

The "12 Principles of Animation", which were developed by Walt Disney Studio in the 1930s (Johnston and Thomas, 1995), are still a valid tool for designing movement as transition from one shape to another, adhering to basic laws of physics as well as emotional timing and character appeal. More recently, Strohmeier *et al.* (2016) have explored the link between the shapes of a flexible surface and emotions, demonstrating that movement might be used to convey messages with emotional content. Similarly, design guidelines can be formulated for light and color shape changing.

Secondly, the behavioral focus recalls the human capability for signification and assignment, known as "attribution" and defined in social psychology as the faculty of being able to explain or infer a behavior (Malle, 2011). Through attribution, humans are able to accurately assign and predict certain psychological attributes to external entities which then determine specific social characteristics such as intention, motivation, and purpose.

At a deeper level then touching the affective aspects related to behavior, it is necessary to mention our tendency as observers to place ourselves in an empathic relationship with others, that is, our ability to understand and respond to the emotional states of other agents.

6.6 Exploring the behavior of animated objects: case studies

After defining animate objects and describing our thoughts on the existing literature, we move to the current scenario of research practices to analyze some case studies that fall under this new class of objects. The chosen case studies contain the features we previously identified. The projects were analyzed including interviews with the designers. We have reported on aspects such as the technologies and materials applied, the form and expressivity, the behaviors, as well as the designers' intentions and narratives. Moving beyond pure appearance, we have identified these objects as agents of smart aesthetic experiences, which include augmented perception, relational communication, and empathy (Russo and Ferrara, 2017).

6.6.1 Lift by the design studio Patten Studio, 2017

Let's take a close look at Lift[8] (Fig. 6.1) designed and produced by James Patten and his team. This is an interactive, heat-sensitive, motorless light feature consisting of 24 LED petals attached to a spine. Each petal embeds a microcontroller that receives data from one of six thermal imaging cameras (infrared sensors) in Lift's ceiling mount.

Lift is a good example of system design that applies a smart material (wires of Nitinol, a shape memory alloy commonly called *muscle thread*) and microelectronics jointly to consolidate materials (metals and polymers for the lamp body).

Moreover, it is a good example of smart aesthetics. This animate object has a high expressiveness, mediating animacy through its computational power and material performance. Lift's petals respond to human presence with a movement that looks more natural than mechanical in terms of fluidity and timing. Each petal works in a coordinated way with the others: it reacts to nearby people by fluttering slightly if someone walks beneath it or moving more dramatically in response to wild movements. In these instances, the closer petals move

[8] Lift received the Core77 Award 2017 in the Furniture & Lighting category.

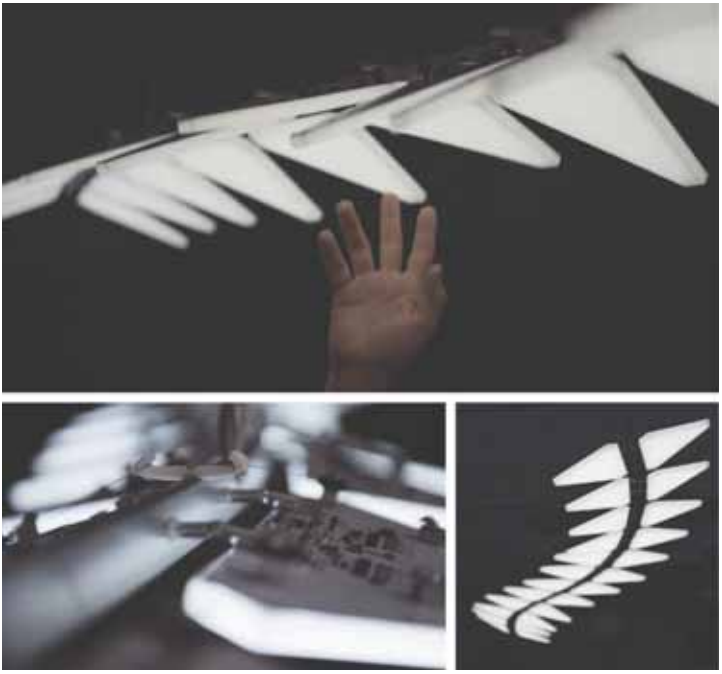

Fig. 6.1 - Lift, interactive light by Patten Studio. Courtesy Patten Studio.

away, as if communicating a feeling of fear. The long central spine of the lamp is composed of pieces like vertebrae, and extends smoothly and asymmetrically, like a snake, resulting in a fluid, organic-looking, and completely silent movement imbuing spaces.

With some of the richness, nuance, and immediacy - the same we would expect from the natural world. […] It will respond as long as those people continue to move around. If those people stop moving, it will gradually return to an idle state, even if they do not leave the room.

Essentially, Lift is seeing human activity by noticing changes in heat in space. […] Environments that acknowledge our presence within them help us to relax - to feel that we belong. Interactivity engages us, helping us to tune into our surroundings, embrace the present moment, and connect to the people we share physical space with (Patten Studio, 2021)[9].

[9] From the interview with James Patten.

In Lift's behavior, we recognize the will to engage the observer in a kinesthetic experience. The smooth shape of the spine from one side to another involves the observer under the petals, who follows the fluent curves and movement. Like a vegetal organism turning its head toward the sun, Lift orients itself toward the people entering its environment (Pattern Studio, 2017).

6.6.2 Opale by Behnaz Farahi, 2017

Opale is a shape-changing interface, also defined as an "emotive garment" (Farahi, 2018) (Fig. 6.2). The focus of this project is the dynamics of social interactions. Opale's behavior is based on its recognition of the basic human emotions that are considered universal and physiologically associated with facial expressions. We normally respond intensely to the expression of an onlooker by adapting our emotional expressions to others' (whether happiness, sadness, surprise, anger, or a neutral expression). This is a neuropsychological process led by mirroring neurons that works as a communication channel.

> The design challenge was to critically explore whether emotions expressed in our social interactions could be represented in a non-verbal way through the motion of a garment (Farahi, 2018).

In technical terms, Opal uses a facial tracking camera that captures the facial expressions of people around and a microcontroller to activate a mechanical system. It is equipped with a pneumatic actuation system capable of generating patterns and various inflation speeds to mimic emotions, thanks to small inflatable silicone pockets. On top of the pockets, thousands of thin fibers are embedded and move by following the pockets' expansions. The movement is inspired by the behavior of animal fur, to which the designer dedicated an attentive study so as to accurately decide the location and orientation of fibers and shape an effect not dissimilar to nature. Subsequently, the fiber distribution on the wearable surface was adapted to the biological structure of the human body and refined in density and weight to make the effect more realistic. The object's behavior-changing creates an aesthetic-emotional experience and influences the behavior of the observer.

Creating a system of exchange «the material then responds physically to the detected emotion in order to establish an effective loop with users» (Farahi, 2017 and 2018).

Fig. 6.2 - Opale by Behnaz Farahi, 2017. Courtesy Behnaz Farahi.

6.6.3 Pinokio by Shanshan Zhou and Adam Ben-Dror, 2012

Pinokio (Fig. 6.3) is an experimental attempt to transform a common artifact into an animated object by designing a behavior through movement. Designed by Shanshan Zhou and Adam Ben-Dror, an anglepoise-type table lamp uses a wide camera to track a user's movements, which are then transformed into the object's movements via a microcontroller. Conceptually, the two designers used body storming and role-playing to analyze and understand the object's possible movements. They then translated the desired behaviors into movements in the joints of Pinokio's arm using inverse IK kinematics[10].

The central concept is to explore if we can evoke empathy in humans when they interact with a machine. We wanted to subvert our "relationship" with a tool from being purely functional, to be empathetic and emotional instead. We wanted to

[10] This is a technique that uses trigonometry to define the spatial movement of multiple parts, commonly used in animation and robotics.

experiment and explore which type of interaction can help to develop a connection between a human and a machine (Zou and Ben-Dro, 2021)[11].

Fig. 6.3 - Pinokio, 2012. Courtesy Shanshan Zhou and Adam Ben-Dror.

Object and user find themselves equal, as the movement of one influences that of the other (Ben-Dro, 2012). The designers add:

> The behaviors we worked on were very simple, they are just enough to give you a sense that this character has some personality, and we didn't want to create a narrative because then it becomes deterministic and more like animatronics that plays a routine.
>
> We worked on simple behaviors such as curiosity (looking around randomly), research (looking for faces, and focusing on people's faces), shyness when people look at Pinokio too long (looks away, ducks down as if to hide), tiredness or boredom (looks down lazily), relaxing (turns off the switch, covers the switch). The key to this aliveness comes down to Pinokio's interaction with humans and the environment: a living creature that responds to random events in the environment (Zou and Ben-Dro, 2021).

[11] From the interview with Shanshan Zhou and Adam Ben-Dror.

6.6.4 Addicted Products, by Simone Rebaudengo with Haque Design + Research, 2012

The last project we are going to present explores gestures and the implication of animate objects being connected. Like in the case of Pinokio, Addicted Products (Fig. 6.4) applies technologies to common objects like toasters, lamps, etc. Using a microprocessor and an Internet connection, the objects become animated and capable of providing a service. The designer imagines a series of toasters connected to a network making decisions autonomously: sending the shopping list to the nearest store, communicating with each other by exchanging information about their use, and even deciding to look for a new user by posting a message on a social network, if they are not suitably used. The designer explains:

> People would apply to an online site for the opportunity to host a toaster, and then the objects themselves would decide where to live based on their perception of being used enough. By being connected their perception of being used, a sort of rudimentary happiness from an object's perspective, was influenced by all the other toasters in the network, creating a sort of peer pressure for objects. Based on their happiness I then programmed a series of behaviors, from a simple toggle movement to attract attention, to tweets to complain to the most extreme behavior for an object: breaking the user/object bond and asking a better user/object to leave and sending a messenger to take it to its new and potentially happier home (Rebaudengo, 2021)[12].

Addicted Products become social agents. Through the movements of the toaster, the user can assign an initial series of behavioral parameters to which are then added all the other relational capacities of the object that manage to influence, not only the nearby environment, but other agents (Rebaudengo, 2012).

[12] From the interview with Simone Rebaudengo.

Fig. 6.4 - Addicted Products by Simone Rebaudengo with Haque Design+Research, 2012. Courtesy Simone Rebaudengo.

6.7 Discussion

From the analysis of the case studies, taking into account the design intention, the user's involvement, and the context in which the objects act, a variety of aesthetic experiences emerge. The relational experiences between user and animate objects mainly refer to:

- The sensory-motion dynamic that happens when behavior primarily affects the senses and the body, stimulating perception, motion, and motivation.
- The sensory-emotion dynamic that overcomes the body stimulation with an empathic relation and emotions coming from the process of attribution, and mainly depends on the coordination of shape-changing in time and space.
- The cognitive-behavioral dynamic, which no longer concerns just the relationship with the object through motion, but also affects cognitive processes.
- The ethical dynamic related to sense-making and reasoning that arrive at ethical judgments.

The dynamics presented are actually various traits of the entire user experience, which contains sensory and ethical traits on opposite sides. In fact, the aesthetic experience is like a continuum in which those dynamics are all present to different degrees, creating an impact at an emotional and a cognitive level, encoding new attitudes, feedback, gestures, and communicative issues.

A similar distinction can be made with regard to the spheres involved, namely the individual and the social.

In the individual sphere the process of adapting behaviors and the relational experience are primarily binary between users and objects and vice-versa. The social sphere involves multiple agents, both human and other animate objects. The process of adapting behaviors is no longer binary but relates to a wide network.

For instance, in the case of Lift and Pinokio, the aesthetic experience involves sensory-motor and sensory-emotion dynamics in the surrounding space, although in different ways.

Lift richly occupies the surrounding space with its presence and behavior, interacting with the observer, who is quickly emotionally caught up in the game between fluid forms and the coordinated time of movements. The kinetics of Lift is linked to that of people in the surrounding space. Each petal responds by moving according to the movement of the observers and reacting sequentially. The design of the long central spine sinuously accompanies the movement of the petals and distributes them within the space. Lift seems to understand and communicate emotions of happiness and fear through its petals' kinetic speed. Shapes and movements together recall natural organisms and provoke empathy in the user, who becomes almost a playmate.

Pinokio involves the user's personal space in a more invasive way, acting out a binary sensory-motor dynamics. The object, initially quiet, starts to move when turned on. Its kinetisms appear like a waking-up and then a seeking of an intimate relationship with the user, who is also influenced by the object's animacy. Moreover, Pinokio expresses curiosity about its user and even demands attention, modulating movements through its articulated arms and the rotation of its head. It extends and contracts, depending on the proximity of the user's face. Even in this case, shape-changings create an empathic response from a user who looks like a shy and curious playmate.

In the case of Opale and Addicted Products, a critical intent involves the body, mind, and society. In these projects the cognitive dynamics seem to be stronger, and the involvement shifts from the individual sphere of a user toward a social sphere.

Emotions seen as social dynamics are the focus of Opale. The designer reflects on the effects of our unconscious facial expression and our body movements related to emotions and imagines a wearable appendix that can empathize with the onlookers.

Emotions are detected and expressed by the object, and through them, Opale involves the user and people around in a behavioral loop with their bodily reactions and, consequently, their minds. Movement depends on perceived emotions and their expression in turn influences movement again.

In the Addicted Products experiment, we recognize a strong ethical-social dynamic. In this project, the designer imagines a society in which there are self-motivated objects with independence, considering both the positive and problematic aspects. The objects' behavior consists in gesture-like movement able to communicate emotion to users, such as moving its lever frantically to complain. This makes objects capable of organizing themselves to respond to problems of consumption and circularity. The designer uses them to try to give an answer to a social and ethical problem, that of production and waste. We add a scheme to visualize the relational dynamics that characterize the aesthetic experience with animate objects referred to in the four case studies (Fig. 6.5).

6.8 Conclusions

Through the analysis of the aforementioned theories and case studies, it has been possible to define the new class of *animate objects* and characterize behavior as a new parameter for reframing objects' smartness in the ongoing process of *phygitalization* of our ambient.

Animate objects, with their capability for shapeshifting, processing data, independence, and pro-activity, express behaviors. These directly influence human behaviors, including our perception, attention, motivation, and, in general, our decision-making capabilities.

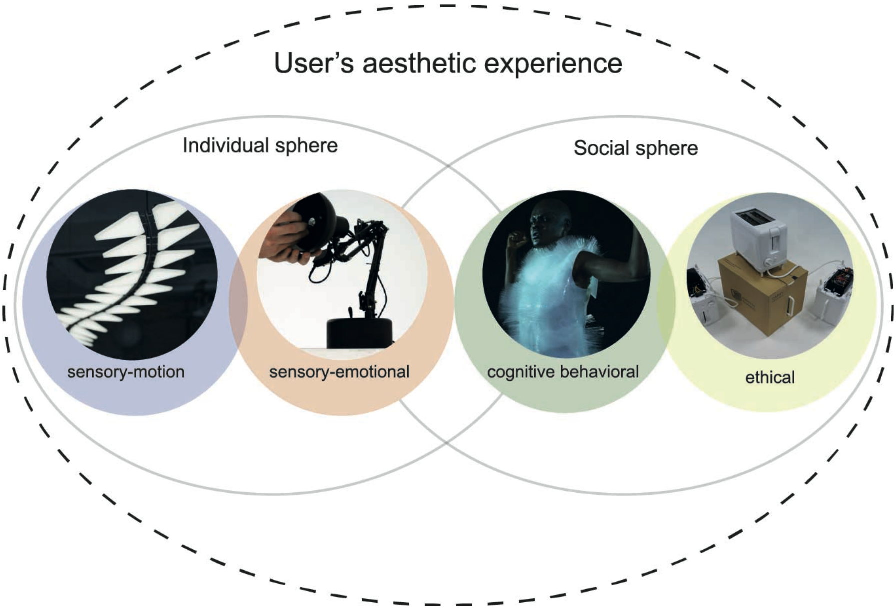

Fig. 6.5 - Scheme of relational dynamics that characterize the aesthetic experience with our four chosen animate objects.

This means that they both stimulate our senses and our cognition, establishing relational qualities in which objects' meaning and value are built.

Through the case studies, we tried to offer a phenomenological taste, albeit minimal, of the current research practices on animate objects. These include common objects (toasters, lamps, clothes, etc.) with a primary function accompanied by a second one that adds qualities to the experience resulting from the object's presence and use.

This scenario is comparable to neither computers nor robots in terms of complexity of the technical functionality or efficiency of the tasks. From Alain Turing's (Turing, 1950) foresight that machines would become more effective if they became credible companions, we shift to the philosophy of "meaningful presence", in which common everyday objects become machines to improve our lives from an ecological point of view. Their presence is «part of who we are, how we live and how we express ourselves» (Hallnäs and Redstrom, 2002, p. 121) - and not just. Animate objects carry affective relationships in the everyday experiences through which we assign meaning as well as value to life.

We believe that the aspects presented so far are of considerable importance, in view of wider reflections on product innovation. They can help us understand the phygital evolution of our environment, with its strengths but also difficulties, and open possibilities of choice.

Today's, objects' behaviors, jointly with the use of time and space, are the central parameters for designing animate objects. The latter represent a design challenge that requires further interdisciplinary research. We believe that the behavioral characteristics of animate objects must be explored and designed in the light of physical variables that relate to shape-changing, in terms of changes in form, dimension, density, light, and color in time.

We strongly encourage further exploration of behaviors in future research.

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7. Reframing the domestic smartness. Artificial intelligence between utopia and dystopia

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Abstract

With AI spreading in domestic environments, the space of the house can acquire new meanings, functions and unlock new possibilities. The digital realm can pervade physical spaces to better take care of the inhabitants of the house. However, how are private domains going to evolve to embrace the potentialities and changes that AI is offering and play a crucial role in developing our well-being?

These practices are at an embryonic phase, and not enough reflections are being made in the design community as they are missing the tools and methods to deal with AI. Nevertheless, the design discipline might translate its expertise into this trending technological field, fostering concrete answers and reasonable solutions for a new way of inhabiting the domestic environment.

Accordingly, the primary purpose of this chapter is to stimulate a conversation about this topic in the design community. To drive the investigation and trigger critical reflections, six near future scenarios, in the form Science Fiction Prototypes (SFPs), are envisioned. They are rooted in the convergence of psychology, design, and AI, revolving around theories of emotions to impact human beings beneficially. Then, a survey, including the evaluation of four of the SFPs, is presented to advance the discussion further and pave the way towards a designerly perspective on AI systems for the domestic environment.

7.1 Domestic spaces between physical and digital: a possibility for design

The time for physical spaces to hybridize with the digital realm has already arrived. Smart speakers integrating virtual assistants represent the first widespread materialization of AI in the domestic environment, and they are a continuously increasing trend. Installed smart speakers are globally forecast to reach 640 million by 2024 - doubling the 320 million in 2020. Additionally, it is more and more frequent to encounter other AI-enhanced objects in our houses: lights, thermostats, doorbells, and even showers, while robots - varying from domestic assistants to pet substitutes - are multiplying (Hitti, 2020). Then, the road to a paradigm shift in ambient computing is paved.

However, the public responds with a mix of contrasting sentiments. On the one side, there is hype and excitement for novelty. On the other, excluding the anxiety generated by filmic worlds overwhelmed by robots, disappointment and frustration are the most frequent sentiments characterizing the use of smart speakers. The design of these devices is one of the main causes: a lack of understanding produced by underlying invisible operations (Norman, 2004), issues in essential elements of interaction like discoverability and proper exploitation of functions (Kinsella, 2018; White, 2018), and the unfulfilled promises made by advertising campaigns make smart speakers miserably fall below expectations.

Indeed, a positive impact of technology on people's mood and life is key: Norman (2004) states that it should bring richness and enjoyment. Aware of that, brands delivering AI-enhanced products are leveraging emotional aspects in their commercials. Accordingly, Amazon Echo is a tool to connect people or just the evolution of a human mate. At the same time, Google, emblematically states "You make a house a home. We make a home a nest", overshadowing the product by highlighting people's different emotional states at home.

The reality, though, tells us a very different story. Even if no deep investigations addressed smart speakers' emotional impact, especially in the long run, we could intuitively compare them with design theories related to (positive) emotions to understand that they need further development. As anticipated, following Khaslavsky and Shedroff's principles of the seductive power of design (1999), they excel in the enticement step with attractive promises, but miserably fail in maintaining them and in making a memorable experience. Likely, whether they respond to an idea of novelty, favorably preserving the quite familiar aesthetic of a speaker, they often require some effort to perform a task, contradicting the first and overarching beneficial feature Hekkert (2006) recognizes. As well, problems arise when it comes to the meaning of the experience, as it is difficult for them to respond to personal significance, virtuous (Desmet and Pohlmeyer, 2013), reflective (Norman, 2004), psychological, or ideological qualities (Jordan, 2000), even marking a rejection of sensuous curiosity and pleasure (Spallazzo, Sciannamè and Ceconello, 2019).

These limitations, accentuated by the daily relevance they have in the domestic sphere, underline how the materialization of AI represents a field full of possibilities for design. For example, one possible area for intervention is humanizing a technology that still seems too far from people. For that, emotional intelligence could play a relevant role. Indeed, as Minsky (2007) states, we need to equip machines with different reasoning processes, and emotions can be considered ways to think we may use to increase our resourcefulness.

7.2 Setting the space for a designerly discussion: our method

The conceptual exploration moves from the intersection of design and AI with human sciences, psychology in particular, trying to overcome the mental restrictions that impede disruptive advancements. Different theories about emotions have been adopted as literal guidelines to orientate the design process and stimulate critical thinking as a sort of exercise in style. Sharing the spirit that drove Raymond Queneau (1947/2007) to experiment with literary variations of speech, we activated the creative engine towards unconventional homes for human well-being. Meanwhile, we collected different pictures that portray alternative futures and embody the core principles of the currents of thought they stand for.

As a result, the outcomes have been experimentally employed to instill a discussion in the design community.

Below, the two main phases of the investigation are depicted.

7.2.1 Science Fiction Prototypes

Future-focused thinking is one of the primary activities of design, especially when related to emerging technology research and the HCI field. For this purpose, the method of science fiction prototyping has been adopted. SFP is considered an embodiment of the third wave of design and HCI practices and aims at capturing the essence of culture, emotion, and experiences, emphasizing the reflective role of the designer in HCI processes (Kymäläinen, 2016). According to Dourish and Bell (2014), Science Fiction Prototypes (SFPs) as tools for design research could not only anticipate but actively shape the technological futures. In this context, SFPs are employed according to Keinonen's model of design-oriented research (2006) as artifacts that may "open new spaces for design", triggering critical thoughts and further speculations about the topic. In a reinterpretation of his model, here the phenomenon to be analyzed (field of research) is AI in the domestic environment, while the framing for interpretation (lying in the field of psychology) are positive emotions, conveying focus and creativity to HCI. Design, instead, maintains its overlapping role to enable the communication between the other fields and brings, as an added value, its expertise to deal with the moment of drunkenness characterizing the introduction of new technology (Antonelli, 2018).

The scenario building is based on Johnson's steps to create an SFP (2011), which is accordingly articulated in (i) technology enabling the scenario and set up of the world, (ii) scientific inflection point - which dramatic change marks the transition to a new progressive scenario?, (iii) implications and ramification of the technology for the world, (iv) human inflection point - how people's life is modified?, (v) implications, solution or lessons learned - judgments are intendedly avoided not to influence the reader. In the following, SFPs are presented in a more narrative style, still covering all the elements. Hence, six scenarios portray more or less near future AI-enhanced houses: (1) the physiological house, (2) the neurological house; (3) the cognitive house, (4) the activity house, (5) the hedonic house, (6) the eudemonic house. According to a specific theoretical conception, they are deliberately designed for people's well-being, explained at the beginning of each SFP. In particular: (1), (2), and (3) address the issue in the most general sense and from a causal perspective; (5) and (6) express possible ways to pursue positive emotions, while (4) lies in-between. The outcomes are intentionally hyperbolic to stress their characteristics, and they are flawed with an individual-centered perspective, reflecting the ego-centric character of the psychological theories. Moreover, they try to highlight the critical points of the technology, autonomy, adaptivity, and the resulting possibilities.

1. The physiological house. Commonly accepted theories assert that emotions and the physiological responses manifested by human bodies are patently interrelated. In some of the earliest emotion theories of modern psychology, physiological responses produce emotional behaviors, as the Peripheral Theory exemplifies (James, 1884); or they just co-occur, it is the case of Cannon-Bard Theory (Lindzey, Thompson and Spring, 1991). Either way, modifications of skin conductivity, body temperature, heart rate, rhythm, blood pressure, and other possible reactions, if well balanced with contextual information, can make emotions measurable.

From these premises stems the physiological house. Provided with a ubiquitous AI system connected to all the smart appliances of the house, it can adapt the environment to people's specific needs. Here, *house-bands* represent the core of the mutual human-home interaction. They measure and keep track of people's physiological parameters, send the data to the house's AI system, and become means of communication by displaying messages. A period of training in which the house learns to understand how its users show their feelings and how they react to different situations by triangulating physiological responses with personal and contextual information is inevitable. Then, as a caring mother, the house ensures that, once at home, one finds its living space perfectly settled: with the right temperature, lights, music, just to name a few. Of course, in the beginning, some misunderstandings might happen. For instance, if one gets scared watching a horror

Fig. 7.1 - SFPs in the form of six future houses. Illustrations by Sara Sciannamè.

movie, the house may turn on the lights and suggest him/her to call someone not to stay alone. However, despite the training time and the massive amount of power and digital/physical space to store data worldwide, physiological houses can be perfectly efficient in tailoring themselves for human well-being.

2. The neurological house. Emotional responses can also be attributed to the internal activity of the brain. Neurological theories suggest that emotions arise in the limbic system (Picard, 1997). Activating the amygdala, the anterior cingulate, or the prefrontal and somatosensory cortices (Damasio, 1994), emotions are an observable phenomenon: they leave a neural signature, identifiable through fMRI (Functional Magnetic Resonance Imaging) as a distributed pattern of activity (Kassam *et al.*, 2013).

Then, monitoring and triggering electrical impulses in the brain, the neurological house can affect people's mental wellness. For this purpose, the house's AI system and its host are in a sort of symbiosis, connected through minuscule electrode threads implanted in the brain. These collect data that the house reads, analyses, and responds to, directly stimulating the appropriate part of the brain to reproduce positive emotional patterns - similarly to the neurologist Duchenne de Boulogne eliciting emotion-related facial expressions by applying faradic shock on facial muscles (Duchenne, 1876). As a positive state of mind is constantly artificially induced through the brain implant, not much is needed inside the house to reach well-being. Indeed, furnishings and decorations become superfluous, and only the survival-related equipment finds a place in the neurological house. Not depending on material solutions, people's status is redefined: their finances are increased, as superficial goods or services have no longer use; bad habits fulfilling secondary needs, like midnight snacks, are a forgotten problem, as the right stimulus can quiet the craving; and some health problems, like obesity or drug addiction, can be easily prevented. Nonetheless, the electrical response to problems and desires hinders people from doing anything non-related to subsistence.

3. The cognitive house. Cognitive theories of emotions indicate reasoning as determining emotional behavior in two main ways. On the one hand, an event is appraised as beneficial, non-relevant, or harmful before a suitable emotion is elicited (Lazarus, 1991); on the other, when we experience an event that causes physiological arousal, the resulting emotion depends on the motivation that our cognitive process recognizes (Schachter and Singer, 1962). If no explanation can be found, we search the environment for clues for labeling the physiological response. As emerged in an experiment (Schachter and Singer, 1962), people who could not understand that physiological responses of their bodies depended on epinephrine injections could be emotionally manipulated with induced cognition towards euphoria or anger.

Following this logic, the cognitive house's AI system, equipped with cameras and managing all environmental facilities, manipulates people's internal appraisal of events by staging favorable contextual conditions if it detects good behaviors or adverse circumstances if it spots bad ones. The objective is to parallel actions with positive or negative emotions according to whether they enable well-being or not. The parameters for the distinction between good and bad are whether based on acknowledged notions about people's health, explicitly customized according to the hosts' goals and apprehended over time by observing their external manifestation of emotions (body language, voice tone).

Then, the house acts like a stubborn and despotic educator. If one wants to get in shape, the house can low the temperature and make the lights colder to infer discomfort as (s)he eats sweets or turn on energetic music to celebrate an exercise session. Either if the user perceives the intentions of the house or not, (s)he is encouraged to follow the right path. Though the motivational process does not have immediate results, people can quit early or endure and reach their goals. In any case, AI finding a balance between physical (health) and psychological well-being (happiness) is a real challenge.

4. The activity house. Even if not explicitly, Activity Theory suggests that emotions proceed from experience, and they are triggered by subject-object activities, intended as purposeful and transformative (Kaptelinin, 2014). In particular, Csikszentmihalyi (1990) identified the highest level of well-being as flow: the condition of being immersed in an activity balancing one's skills and perceived challenge.

The activity house, as the name implies, advocates an active and meaningful home life. As a conversational agent, it proactively proposes to people what to do according to their characters, lifestyles, objectives, skills, and external events so that they can effortlessly achieve happiness. For this purpose, the AI system connected to the house should know the owners better than themselves. Hence, it needs to be deployed on their devices to unobtrusively monitor what happens to the users throughout the day (via microphone, calendar, email, messages). Keeping track of the daily routines and learning from the constant monitoring of the hosts' behaviors and reactions, the activity house can autonomously organize people's time and encounter their procedural preferences (granting complete transparency to planning-maniacs or surprising improvisation-lovers).

At least at home, people will not need to worry about what to do, as their customized managing system can suggest relaxing with a yoga session after a tough day or trying a new recipe for a personal sense of fulfillment. It can also guide the inhabitants throughout their activities by warning them in case of wrongdoing and with visual supports. In such a house, time-waste is no longer a cause of frustration, but deferring organizational matters can become indispensable over time.

5. The hedonic house. Emblematically embodying the hedonistic tradition - for which life is a quest for pleasure for pleasure's sake, while negative affect is avoided (Deci and Ryan, 2008) - this house is filled with appealing appliances, autonomously performing their duties and attesting their functioning as an enjoyable event. For instance, a laundry machine directly linked to the wardrobe manages dirty and clean laundry, deciding when to wash or refresh clothes. While in operation, it gives off a fresh scent to please people with positive sensations and communicate its operational status.

Of course, space is appropriately configured to facilitate the autonomy of the appliances. Plus, a control room hosts the necessary equipment for the autonomous (software and hardware) updating of the self-sufficient machines. This kind of well-being is ephemeral in nature, as demonstrated by the treadmill metaphor (Brickman and Campbell, 1971): people in constant pursuit of pleasure are like rats on a treadmill. They keep running, but their condition will never change. Therefore, as soon as people get used to their functions and positive elicitations, the home appliances need to evolve, modifying their functions and feedbacks.

Indeed, the house will be a personal paradise, entirely at the service of its inhabitants: it shelters them from burdensome tasks and conveys pleasure. If they need something, people just have to ask. It may be the next frontier of consumerism.

6. The eudemonic house. Contrasting with the previous philosophy, Eudemonic Theories focus on living life in a full and deeply satisfying way, pursuing personal development and meaning (Deci and Ryan, 2008). This conceptualization does not imply that happiness coincides with positive emotions. Instead, it considers well-being as a process of fulfilling or realizing one's true nature, not as an outcome or end state. High-level targets are set, including self-acceptance, positive relations with others, autonomy, environmental mastery, purpose in life, and personal growth (Ryff, 1989). For this reason, the eudemonic house must act as a conscience, leaving people total control over their choices.

The integrated AI system is linked with sensors to perceive human beings and with enhanced surfaces to communicate with them. In a proactive and shared perceptual (Marti, 2010) approach, when the house detects the presence of a user, it manifests its interactive intention using any available surface and starts it without being prompted. The eudemonic house can portray questions, make suggestions or instill reflections, with the only aim to help its inhabitants' increase their personal values. The interaction is smooth and subtle, and it depends on the user whether to embrace the cues or not. Indeed, impositions are senseless as without voluntariness, involvement is impeded, yet freedom can thwart the AI system's efforts.

7.2.3 The survey

Subsequently to their generation, four of the SFPs have been submitted to a sample of 12 design researchers from the Department of Design of Politecnico di Milano (selected as experts in different areas of interest: technology, well-being, spatial or critical and future related), in the form of an online questionnaire. This preliminary research is chiefly intended to gather ideas from a design-oriented perspective about how AI can benefit the domestic environment and evaluate the performance of the SFPs coherently with that purpose.

Primarily due to a reasonable estimate for completing the questionnaire in under 15 minutes, two SFPs, namely the neurological and the cognitive house, were not included in the selection. Both were expected to elicit reservations from respondents as the former does not present rich stimuli in terms of spatial design, while the latter is not of immediate understanding. The others, instead, portray a variety of design possibilities, each insisting on peculiar data collection and interaction modalities.

The survey is structured on three main streams of information (i) defining the current position of designers/researchers towards the spreading of AI, (ii) assessing the SFPs, (iii) deriving designerly projections. In this context, no practical design repercussion has been encouraged: the aim was to identify designers' concerns on the topic following Desmet and Hekkert's model (2001), according to which concerns can be delineated as attitude (personal disposition), goals (what they want), and standards (how they expect things to be).

(i) To learn how the respondents are disposed toward AI, a straightforward question opens the questionnaire. It distinguishes four possible attitudes: digital utopians, beneficial-AI supporters, techno-skeptics, and prophets of doom, adapting Tegmark's categorization (2017) with the addition of a more pessimist position. Moreover, further qualitative indications can be inferred from all the answers.

(ii) To gather the most immediate reactions, the SFPs' evaluation articulates on two different levels: the perceived cognitive appraisal of the scenario and the elicited affective response. First, the respondents are asked to distinguish whether the imagined house represents a utopia, a starting point to do better, the premise for deviousness, or a dystopia, allowing the inference of the designer's major concerns throughout the entire set of appraisals. Then, an affective evaluation is required. The research's thematic connotation drove this choice along with the fact that it is largely considered effective in providing an instinctive and mutually understandable assessment of such a complex subject. To this end, the model of the Emocards (Desmet, Overbeeke and Tax, 2001) has been selected out of the analysis of several emotion-related UX evaluation methods (Spallazzo *et al.*, 2021). It is based on the circumplex model (Russell, 1980), representing emotions on a bidimensional scale, with valence/pleasantness on the horizontal axis and arousal on the vertical one. This categorization, together with the figurative representation of the emotional expressions, saves respondents the trouble of verbalizing their affective response: a commonly recognized challenging task requiring cognitive involvement, which may influence the response itself (Desmet, Overbeeke and Tax, 2001). At the same time, it does not suggest categorical emotions that can be easily perceived as out-of-context, but it offers sufficiently generic yet grained possibilities. To better frame the information, a motivation for the choice is also required.

(iii) Finally, broader reflections are encouraged to supplement the picture of designers' concerns about the spreading of AI in the domestic context. For brevity in such a wide discourse, two main issues are brought to attention: the most valuable AI capabilities towards beneficial outcomes and the fundamental principles to consider in designing AI-infused products for the domestic environment (this question was optional). This section is intended to collect indications about the respondents' goals and standards. Consequently, it represents an effective means to outline a preliminary path towards a designerly way to develop genuinely beneficial AI systems.

7.3 Opening a designerly conversation: initial reflections

The survey reveals that the solicited designers share an overall positive attitude towards AI (i). The direct question shows that 10 out of 12 respondents agree that "AI may be beneficial, but crucial issues need to be addressed in advance" (beneficial-AI supporters). One sustains that "a new, enriched and enlightened era is approaching for humans" (digital utopian). Instead, the other one openly takes a pessimistic position: "AI is going to improve but we won't be able to handle unintended negative consequences" (prophet of doom). Starting from the latter for closer observation, we can notice linearity in the attitude: from a negative perception for the future of AI emerges a very conservative approach. Each scenario is firmly repulsed, and only a slight improvement of current technologies is an acceptable future development, denoting a strict closure of mind towards the topic. On the diametrically opposite side, the digital utopian's thought evolves throughout the questionnaire. Mainly maintaining a positive attitude, (s)he develops critical angles and sets boundaries that should not be crossed. Finally, within the most accredited and cautious attitude, diversity seems to be the predominant feature. Each SFP is carefully evaluated, with no recurrent assumption influencing the judgment. In this way, every scenario allows raising different considerations and, eventually, a nuanced picture can be framed. Critical thinking unites those who positively perceive AI as an asset for the future, a quality generally recognized as distinctive for designers.

Going into the assessment of the SFPs (ii), interesting insights can be drawn by analyzing the three required contributes (cognitive appraisal, affective response, and motivation) separately and then confronting them to spot discrepancies. Due to the conciseness of the responses and the limited number of respondents, this evaluation is purely qualitative yet systematic.

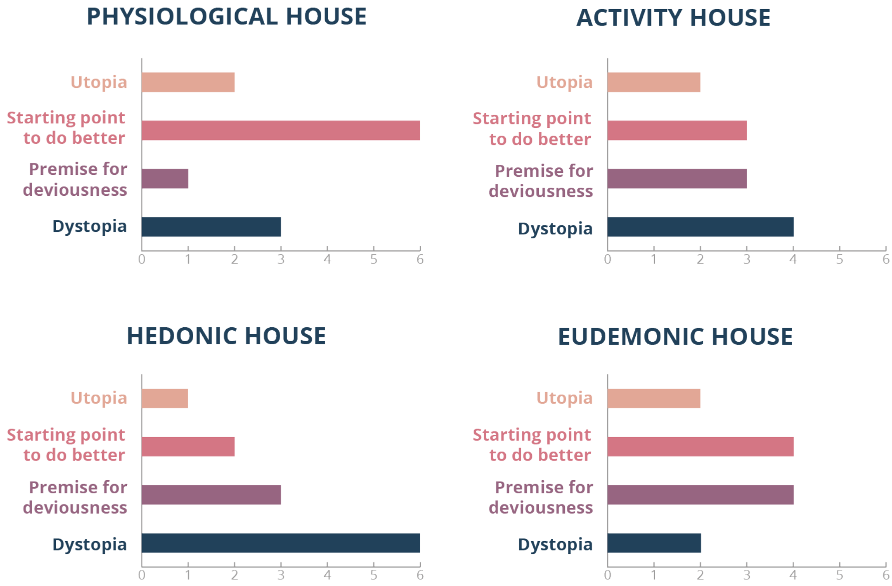

Fig. 7.2 - Cognitive appraisal of the SFPs.

7.3.1 The physiological house: a balanced solution

The physiological house has the most balanced distribution of positive and negative opinions, and within these factions, the positions are convincingly emphasized. If the general judgment tends towards a constructive vision of the system adapting the environment according to people's physiological parameters, the emotional reactions reach an equilibrium. On the positive side, the house is perceived as an improvement. It is praised as great, wonderful, helpful, primarily because of its capability to adapt - matching personal needs and desires - and to automate tasks, bringing comfort and saving time. Some concerns about the preservation of human agency and data protection arise. On the other, negative impressions primarily revolve around the concept of autonomy, intended both as a harmful capability for the AI system and as a lack of control for people. Additional comments mark privacy, transparency, and non-necessity as problematic issues. Probably, the ambivalent perception depends on the fact that the house deals with personal data, but without interfering in the inhabitants' private lives, it just manages contextual conditions. Then, the position of respondent may interchangeably focus on the convenience or the autonomy of the system.

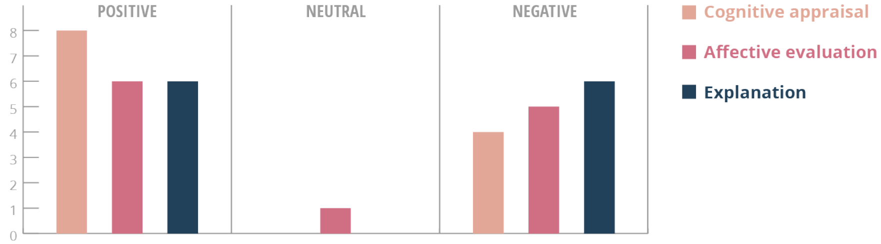

Fig. 7.3 - Qualitative categorization of the physiological house's assessments.

7.3.2 The activity house: practical but despotic

The activity house, instead, sets the beginning of a general tendency towards unfavorable assessments. Already slightly intelligible from the cognitive discrimination (even if the responses are quite assorted), a predominant uneasiness is manifested by the affective reactions and explanations. Positive statements are more tepid than the previous, with less enthusiastic terms depicting the house as pleasant, likable, interesting, and helpful. What has been chiefly endorsed is the practical aspect it embeds: it grants a better organization and possible beneficial health implications. Inevitably, though, criticisms concern the obtrusiveness of the system and the dependency it may instill. The same issues are reinforced in the negative observations. Human dominance and freedom are defended against succumbing to a trespassing technology: it makes people "feel watched" and question the meaning of being human, which, according to the respondents, cannot be defined in an exclusively pragmatic perspective. In this case, the AI systems need to intrude people's lives, with the activity log being the only source for it to be an effective counselor. Surprisingly, for design academics exposed to the discussion about privacy and trustworthiness issues, what bothered them the most is the feeling of deprivation of a controlling role.

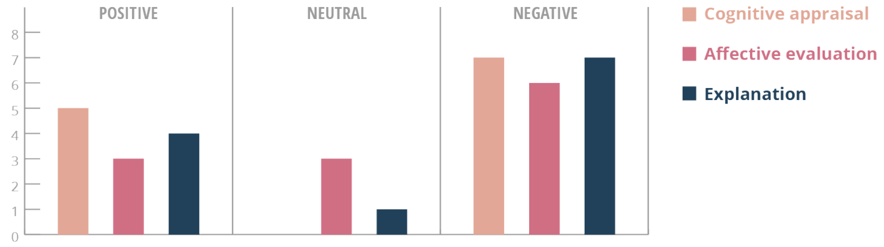

Fig. 7.4 - Qualitative categorization of the activity house's assessments.

7.3.3 The hedonic house: too much

The sensation is amplified in the hedonic house. Mainly appearing as a dystopia, it finds quite a united hostile front. The reaction is almost indescribable, with more than one respondent emblematically stating "it is too much". Again, the figuration of this house is rejected, as it could take pieces of humanity away. Major fears are related to the autonomy of the person over machines and the isolation and dissatisfaction that a compliant behavior may produce. In return, responses bring out a will of escape from the house itself as it is no place to find entertainment, and the word "afraid" appears twice. Two are the positive comments on the hedonic house, appreciated for avoiding burdensome tasks but still arising questions about the actual necessity of a functional and unconventionally entertaining system. Indeed, here the practical aspect of the self-sufficient house seems to pass overlooked, and just the protagonist behavior, optimized to provide pleasure, is on the spot and not gaining popularity.

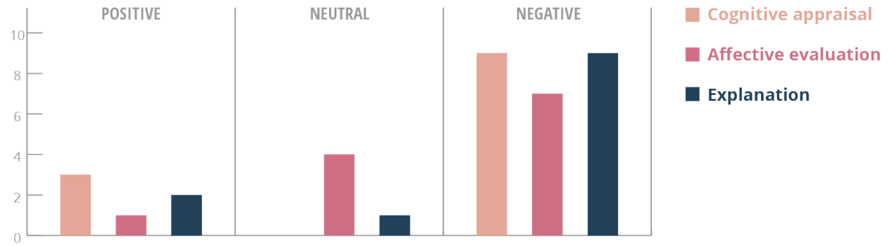

Fig. 7.5 - Qualitative categorization of the hedonic house's assessments.

7.3.4 The eudemonic house: intruding human life

Ultimately, the eudemonic house shows an apparent balance both in the cognitive appraisal and affective evaluation, but this is betrayed in the more articulated explanations, leaning, once again, towards a negative criticism. In the few positive opinions, the tone is still cool and the responses are scarcely eloquent. Only one envisions positive repercussions for (physical) health, while human agency and caution about not confining oneself to the home are advocated. However, they portray the house in terms like good, interesting, beneficial, preferable, useful, and non-intrusive. The latter, though, is a controversial point as intrusiveness is a recurrent motivation in adverse comments. Here, the eudemonic house even causes people to feel invaded in their freedom, manipulated, judged, and puppets in the hands of a mediating, directing, and managing system. Once again, human independence is central, and someone, exhausted, states that (s)he associates psycho-physical well-being to nature and open air. Then, no matter how much the narrative was underlying the discrete, constructive and supportive role of the house, at this point, a sort of oppression seems the predominant impression. However, some usefulness is recognized: the system can be pleasant and of great help in specific situations, such as managing complex problems and entertaining the masses.

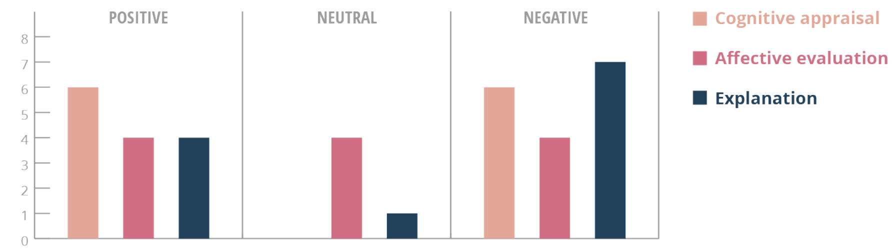

Fig. 7.6 - Qualitative categorization of the eudemonic house's assessments.

Fig. 7.7 - Affective evaluation of the SFPs.

7.4 Designerly reflections and implications

Finally, the respondents' considerations (iii) and concerns are outlined to understand what could drive a designerly reflection on the development of AI systems for the domestic space.

Lacking a proper explanation of the proposed potentialities of AI (automating, enhancing, empowering, specializing, and inspiring), they have been interpreted in multiple ways, and the argumentations about AI capabilities and principles tend to overlap. Though, when envisioning the value of AI systems in everyday life, they are framed as supporters of human activities, taking on the burden of demanding, unpleasant, long, and repetitive tasks in the light of convenience. The core message emerging loudly throughout the questionnaire is the essentiality for humans to maintain autonomy and control their own lives, choices, and the machines themselves. This requirement directly prompts an interrogation about the ontological meaning of human existence, which, in turn, leads back to the key issue of this experimentation (How can AI be beneficial for humans? What can humans reach maximum well-being? What is the purpose of life?). An escalation culminating in a complex philosophical discussion that goes beyond the purpose of this work and would demand the participation of different parties. From a UX standpoint, what needs to be considered in the design process and overtly communicated to the final user is human agency over products and services integrating AI systems.

To complete the picture of the beneficial features of AI, one also enlists customization, while another amplifies the individual dimension in an eco-systemic sense, extending the technological potentialities in the service of big challenges humanity has to face: the preservation of the environment, health, human rights.

Following the principles that should guide the development of AI systems, a responsible approach is mandatory. Ethical behavior, moral responsibilities, and attention to privacy are recommended, but they appear more like a standard to the responding designers. Issues about collecting and using data were only seldom cited while assessing the scenarios, suggesting that this is important yet secondary in relation to more existential matters.

Eventually, also values closer to UX practices have been depicted. It is the case of unobtrusiveness (systems should operate without invading the natural flow of human activities), embodiment (currently, AI systems are often invisibly embedded in products and services and interaction is poorly designed), adaptivity, and transferability (technology should support contemporary tendencies and necessities like nomadism and temporary housing, pushing customization to a next level).

An additional, curious inferring from the survey is the personification of the AI systems described in the SFPs. They are frequently referred to as agents: “artificial entities”, “not my friends”, “with a form of judgment” are some humanized epithets that have been used. Indeed it is not distinct from how Russel and Norvig technically address AI systems in their well-known textbook (2020), but this has more profound implications for interaction and UX design. The concept of products as living objects with which people have relationships, explored by Jordan as the “New Human Factors” paradigm (2000; 2002), has much more resonance when dealing with a technology born to mimic human reasoning. Personifying inanimate objects is a natural inclination, yet a controversial issue when it comes to systems that are misleadingly defined as autonomous entities, learning and adapting over time. Indeed, this may cause some resistance and urgency to demote AI systems to a supporting role.

7.4.1 What the future holds

Although not quantitatively relevant, this preliminary research represents a groundwork for fueling the discussion about the development of AI systems from a designerly perspective. The depicted concerns can be starting points for further, more practical investigations since they can drive the generation of methods and tools for designers to deal with this technology. They can also bring fresh insights to the decision tables.

SFPs have also proven effective in triggering reactions and reflections, leaving room for new applications in focus groups, workshops, or didactic experiences.

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The book explores evolving perspectives on furniture, interior, spatial and architectural design, providing a multifaceted view of how the design discipline and practice deal with the complex and ever-evolving interplay between the physical and the digital realms. It explores the new frontiers of digitally enhanced design, investigating how computation capabilities impact the design discipline and designers' thinking and practice. Today more than ever, the design discipline must cope with the need to absorb technical skills and dialogue with traditionally distant domains. The core competencies in the Human-Computer Interaction field are becoming essential to every design branch: the computational power is entering the design process, modifying how products and spaces are designed, how they are produced, and how they will impact the daily life of users.

The book explores these novel frontiers, proposing captivating portraits of digitally enhanced design possibilities, from tools and processes to expressive potentials.

Industry 4.0 and traditional craftsmanship hybridize in view of a circular and just economy for the furniture sector, imagining new approaches towards the European Green Deal. The sensing capabilities are intertwined with the materials to create a new form of animated objects, proposing a novel design approach beyond the user-centered one. The computational power of lighting design tools is entering the complex BIM methodology, exploring the problematic integration between the two worlds, and proposing solutions to support the design activity. Artificial Intelligence reframes the domestic landscape, thanks to Science Fiction Scenarios, to stimulate reflection on the designer's role in framing utopic/dystopic futures. Finally, data drive the design of adaptive morphologies, exploring the context of computational design with a conceptual framework and reflecting on how robotic design can contribute to architecture.

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