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CIRCULAR ECONOMY PATHWAYS WITH PROGRAMMABLE INTELLIGENT SURFACES AND MATERIALS

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Abstract – *The present study proposes the use of intelligent materials in the design of products, as enforcers of circular economy principles. Intelligent materials can tune their physical properties (electromagnetic, acoustic, mechanical and thermal) by receiving software commands. When incorporated within products and living spaces they can mitigate the resource waste caused by inefficient, partially optimized designs and security concerns. Thus, a circular economy and fast-paced product design become compatible. The study begins by surveying existing artificial materials, outlining their operating principles for controlling their macroscopic physical properties in in real time, demonstrably enabling the micromanagement of vibrations and heat. Then, the study presents the concept of a circular economy and analyzes current related research. Finally, the paper surveys promising synergies between artificial materials and a circular economy across multiple industrial sectors, highlighting considerable gain potentials in an ecological footprint.*

Keywords – Acoustic, circular economy, ecology, electromagnetic, energy conservation, intelligent surfaces, material properties, mechanical, metamaterials, metasurfaces, micromanagement, RIS, security

1. INTRODUCTION

The industrial and electronic revolution has had a tremendous impact on our world at all levels, from the micro to the macro levels. Our everyday lives are dependent on the facilities of industrial production of goods, transportation, communication and computation. At the macroscopic level, the global economy is shaped by the flow of goods and services. However, this revolution was partial and never planned in depth, to account for its ecological sustainability. As a result, the natural resources of the planet are already expended faster than their replenishment rate, while by 2030 the expenditure will be twice the replenishment [1].

Industrial design has been partial due to its fast-paced, antagonistic nature and due to the lack of a central framework for lifecycle management across products. Its fast-paced nature means that a company that offers a product to the market is income-driven, and always insecure about another company getting to the market first. Thus, due to a lack of time, products are only partially optimized: they revolve around the immediate facility, disregarding all the rest, sustainability and security included. This fast pace also alters the environment faster than the reaction time of governments. Legislation and frameworks arrive late, while their enforcement is slow as well. The concept of a circular economy seeks to provide a framework for sustainability at micro, meso and macro-levels [2]. At the micro-level (single product), it may provide directives for a circular product lifecycle. Instead of the traditional, linear order of lifecycle phases, i.e., i) raw resource acquirement, ii) processing and manufacturing, iii) distribution, iv) use and v) disposal, a circular economy aims to minimize resource usage by extending useful product life, thus linking the use phase back to all preceding phases. Accordingly, product design should facilitate four links: i) decomposition to raw materials, ii) reprocessing or refurbishment, iii) redeployment and redistribution, and iv) multiple uses. However, this effort will require extra design and development time from companies, which incurs costs and opposes their fast-paced nature. Thus, novel approaches are necessary to ensure the success of the circular economy concept.

The present work proposes the use of intelligent materials as enforcers of a circular economy in a fast-paced product design. Artificial materials, also known as metamaterials, have engineered physical properties, such as electromagnetic (EM), acoustic and mechanical behaviour. Moreover, they can exhibit properties not found in natural materials, such as a negative refraction index, perfect insulation, etc. Additionally, a recent advancement called the Internet of Materials (IoM) has created artificial materials with software-defined properties that can be controlled in real time [3]. IoM dictates: i) a well-defined programming interface abstracts underlying complexities and allows non-specialists (such as software developers) to incorporate the artificial materials in applications and products, without caring for their inner physics, and ii) a well-defined communication and protocol for inter-networking any artificial material with existing smart devices and systems.

The present study exploits these traits to contribute ways that intelligent materials can strongly facilitate the circular economy objectives. We envisage artificial materials as coatings or structural parts of products, acting as real-time ecological enforcement agents for products across any physical property domain. For instance, electromagnetic interference and unwanted emissions can be harvested by walls coated with electromagnetic metamaterials and be transformed back to usable electrical or mechanical energy [4, 5, 6]. Mechanical metamaterials can micromanage emanated heat and vibrations from motors to recycle it as energy while effectively cooling it. Acoustic metamaterials can surround noisy devices or applied on windows to provide a more silent environment, but to also harvest energy which can be added to the household. A notable trait of all artificial materials is that they are simple structures and, therefore, their production itself can easily follow the aforementioned four principles of circular economy. Moreover, their software-defined nature allows for quickly "patching" the non-ecological parts of new or existing products, without much overhead to the industrial pace. The "patching" may also be deferred in the form of "eco-firmware", distributed via the Internet to ecologically tune a single product or horizontal sets of products. In the following, we provide a methodology creating ecosystems of intelligent materials and propose the micromanaged electromagnetic environments.

The remainder of this paper is as follows. In sections 2 and 3 we present an introduction to artificial materials and the circular economy respectively. Their proposed synergy is studied in section 4. The study is concluded in section 5. It is noted that an early version of this work has been presented in conference form [7].

2. ARTIFICIAL MATERIALS: OPERATING PRINCIPLES AND TRENDS

This section provides the necessary background knowledge on artificial materials, discussing dimensions and composition, operating principles, programmability and inter-networking approaches.

Overview Artificial materials are simple structures created by 3D/2D stackups of basic resonant building blocks, the *meta-atoms*, that offer engineered and tunable physical properties at a macroscopic level. In terms of terminology, 3D stackups are usually denoted as *metamaterials*, while 2D arrangements as *metasurfaces*. Their tunability can refer to any combination of electrical, acoustic, mechanical or thermal physical property.

Electromagnetic metamaterials were the first kind of metamaterials to be proposed and studied, mainly due to the relative ease of manufacturing [8]. They offer tunable surface and volume permeability and permittivity, translating to tunable redirection, absorption, polarization and phase control of impinging waves. The most recent research focus is placed on space-time modulated metasurfaces. Spatial modulation of metasurfaces enables functionalities such as wavefront manipulation, polarization control, and angular momentum conversion. Space-time modulation can allow additional functionalities by exploiting the additional degree of freedom of temporal modulation of the unit cell properties [9]. Applying temporal modulation on coding/digital metasurfaces can lead to the generation of new harmonics, acting as a frequency mixer [10]. In addition, spatio-temporal modulation of the metasurface unit cells can be utilized to allow for nonreciprocal operation [9]. This provides a very interesting alternative to magnetically-biased (and thus cumbersome) and nonlinear (thus depending on the incident intensity) metasurfaces for enabling such advanced functionalities.

Notably, the same principles have been applied to control sound (acoustic metamaterials [11]) and mechanical waves (mechanical metamaterials [12]). With the advent of 3D printing, acoustic and mechanical metamaterials have become easier to manufacture boosting the related research. Acoustic metamaterials can manipulate and re-engineer sound waves in gases, solids and liquids. This control is exerted mainly through the bulk modulus, mass density and chirality. The latter two properties correspond to the electromagnetic permittivity and permeability in EM metamaterials. Related to this are the mechanics of wave propagation in a lattice structure. Also materials have mass, and intrinsic degrees of stiffness. Together these form a resonant system, and the sonic resonance is excited by sonic frequencies (e.g., pulses at audio frequencies). Controlling sonic waves has been extended to unnatural properties, including negative refraction. Mechanical metamaterials can be seen as a super-set of acoustic metamaterials. They too can be designed to exhibit properties which cannot be found in nature. Popular mechanical properties that have been controlled in academic studies include compressibility, contractivity and focusing of mechanical waves. However, the exerted control over vibrations can customized as required by the application scenario.

Thermal manipulation precedes historically the work on all metamaterials, since artificial heat conduction (and cloaking) constitutes a major goal in multiple industrial enterprises [13]. Thermal artificial materials essentially pose structures that restrict the solutions to the heat-conduction equations (which contains two parameters, namely the thermal conductivity and the specific heat capacity), thereby attaining controllable heat dissipation and 'routing'. In specific conditions, it has been shown that parts of metamaterials of this class can completely avoid thermal energy even under direct heating, essentially attaining thermal cloaking [13]. While thermal dissipation is inherently a quantum phenomenon (thus, beyond absolute control at present), it can still be managed to a degree by structuring and stacking materials, i.e., in the sense of thermally-aware mechanical artificial materials.

Metasurfaces can be manufactured with a wide set of processes, ranging from printed circuit boards, to 3D printing and Computerized Numerical Control (CNC) milling [14, 15, 16].

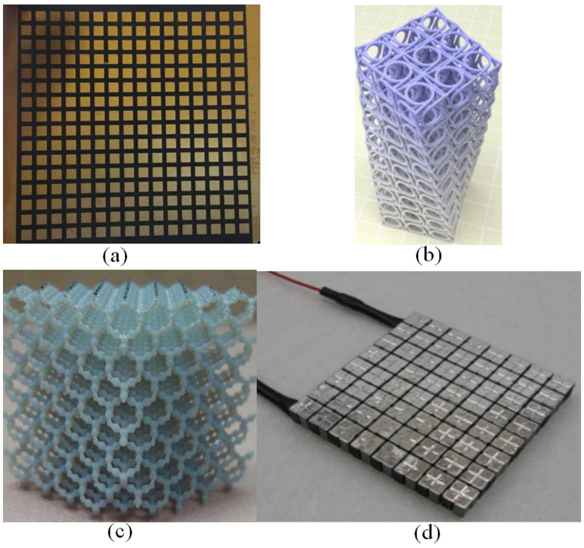
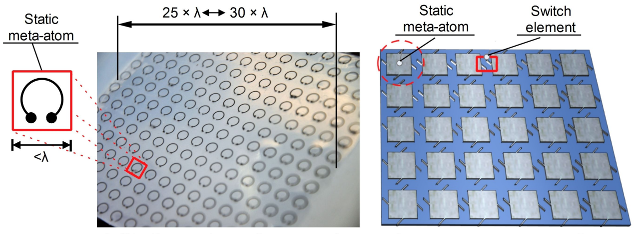


Fig. 1 – Indicative composition of artificial materials: (a) electromagnetic [17] (b) mechanical [18] (c) acoustic [19] (d) thermal [20].



a) Static metasurface design b) Dynamic metasurface

Fig. 2 – Split ring resonators (left) constituted a very common type of static electromagnetic metasurfaces, with fixed macroscopic behaviour. Dynamic designs (right) incorporate switch elements (MEMS, CMOS or other) to offer dynamically tunable electromagnetic behaviour.

Composition All artificial materials follow the same general composition template, with a basic meta-atom structure being repeated to fill a surface or a volume. A neutral material (with regard to the nature of the targeted wave manipulation) acts as a scaffold upon which the meta-atoms are placed. Indicative examples are shown in Fig. 1.

In the electromagnetic material case, and in most usual compositions, the meta-atom is conductive and the substrate is dielectric. Common choices are copper over silicon, printed organic circuits over films, while silver and gold constitute conductors for exotic applications [21]. Other approaches employ graphene, in order to interact with THz-modulated waves [22]. Metasurfaces are able to control EM waves impinging on them, in a frequency span that depends on the overall dimensions. The size of the meta-atom is comparable to the intended interaction wavelength, λ, with $\frac{\lambda}{2}$ constituting a common choice. The thickness of the metasurface is smaller than the interaction wavelength, ranging between $\frac{\lambda}{10} \rightarrow \frac{\lambda}{5}$ as a rule of thumb. Metasurfaces usually comprise several hundreds of meta-atoms, which results in fine-grained control over the EM interaction control. Metamaterials are the 3D counterpart of the concept, and can be perceived as a stack of metasurfaces.

Fig. 2a illustrates a well-studied metasurface design comprising split-ring resonators as the meta-atom pattern. Such classic designs that rely on a static meta-atom, naturally yield a static interaction with EM waves. The need for dynamic alteration of the EM wave control type has given rise to dynamic, programmable metasurfaces, as illustrated in Fig. 2b. Dynamic meta-atoms incorporate phase switching components, such as MEMS or CMOS transistors, which can alter the structure of the meta-atom. Thus, dynamic meta-atoms allow for time-variant EM interaction, while meta-atom alterations may give rise to multifrequency operation [21]. Phase switching components can also be classified into state-preserving or not. For instance, mechanical switches may retain their state and require powering only for state transitions, while semiconductor switches require power to maintain their state.

In the acoustic case, many materials make use of ultra-thin membranes, specifically tailored to dissipate sound [11]. Those membranes, are often preloaded with certain stress caused by a small mass on top of their surface. Some other applications prefer to apply stress through the use of magnets, or have their tension adjusted by fixing their perimeter on a solid structure. All of these techniques aim to control and adjust the vibration characteristics of the structure, dynamic mass density and bulk modulus. Membranes of these structures often come in one or multiple layers depending on the frequency band they aim to induce sound transmission loss. Other acoustic metamaterials employ phononic crystals, which are periodic structures that aim to manipulate sound waves. Their construction methods and materials can greatly vary, depending on the application and the waveband that they are destined to control. The features of these crystals mainly rely on the principle of band gap. At resonance the acoustic waves are allowed to propagate, and at anti-resonance they are not allowed to propagate.

Mechanical metamaterials are generally associated with the Young's modulus, shear modulus, bulk modulus and Poisson's ratio and directly affect the stiffness, rigidity and compressibility of the metamaterial [12]. Most of the metamaterials' applications contribute to impact protection and absorption of electric or magnetic incidents, depending on the topology optimization that can be achieved. Different typologies include nanolattices, chiral and origami patterns, which are usually 3D printed and, once fabricated, changes to them are difficult. Compliant shapes are used as multi-state switching elements, which can commendably turn their rigidity between on and off states, as well as many intermediate states.

Finally, regarding thermal metamaterials, in order for them to be able to steer heat flux, they need to have some anisotropic thermal conductivity [20]. Therefore, layering two isotropic materials with different thermal conductivities, is considered as a way to create a thermal metamaterial. The steering angle of heat flux would be a function of the orientation of the two layered materials in the composite and the bigger the difference between the two conductivities, the bigger the magnitude of the steering effect. There are examples of applications using layered materials in different orientations, using stainless steel and thermal epoxy layers with a large thermal conductivity ratio.

A categorization of artificial materials (for the less common, acoustic, mechanical and thermal domains), per composition and supported functionality is summarized in Fig. 3.

Operating principle The operating principle of artificial materials is given in Fig. 4. The meta-atoms, and their interconnected switch elements in the dynamic case, act as control factors over the waves flowing over and within the material. The total macroscopic response of the material is then derived as the sum of all meta-atom vibrations and waves, and can take completely engineered forms, such as the cross-domain unnatural wave reflection shown in Fig. 4. Engineering the total macroscopic response is a complex process that must account for vibrations and waves directly induced over the material by the incident wave, the vibrations and waves induced in a meta-atom by other meta-atoms, as well as the vibrations and waves flowing inwards or outwards from a meta-atom via the switch elements.

An artificial material can support a wide range of macroscopic interactions, i.e., *wave functions*, which are classified as follows [23]:

- Reflection of an impinging wave, with a given direction of arrival, towards a completely custom direction.
- Refraction of impinging waves via the material towards any inwards direction. Both the reflection and refraction functions can override the outgoing directions predicted by Snell's law. Reflection and refraction functions will jointly be referred to as wave *steering*. In the electromagnetic domain, steering can provide security at the physical layer, by bending waves around unwanted users, completely negating eavesdropping [5].
- Wave absorbing, i.e., ensuring minimal reflected and/or refracted power for impinging waves.

In the electromagnetic case, wave polarizing, i.e., changing the oscillation orientation of the wave's electric and magnetic field, is also possible.

Inter-networking and programmability of artificial materials In general, artificial materials can fully re-engineer the impinging wave, producing a completely custom response-field [24]. IoM offers an incorporation-ready approach to artificial materials [4, 6, 5]. IoM models the wave functions supported by a material as a software API, comprising callbacks with the following general form:

```
outcome←callback(action_type, parameters)
```

where `action_type` defines the type of the wave function (such as `STEER`, `ABSORB`, etc.), accompanied by the necessary parameters to completely define the wanted interaction. Thus, the complexities of metasurface physics are abstracted and hidden, focusing on usability by software developers. Following the IoM paradigm, the macroscopic functionalities of all artificial materials can be exposed in software. Subsequently, they can be easily incorporated to a networked-controlled environment. In order to effectively meet this end, IoM leverages the Network Functions Virtualization (NFV) and Software-Defined Networking (SDN) concepts.

NFV is a novel concept in network design and operation, which seeks to express services offered by a network into building-block components that can be connected (i.e., *chained*) together, to create custom operations on demand. In essence, NFV is a form of well-structured virtualization that abstracts an offered function from the underlying *material* performing the low-level computations. The NFV building blocks are called the Virtual Network Function Components, which are distributed and isolated packages that can be configured, initiated, migrated and destroyed in accordance with a defined workflow or lifecycle. The NFV principles do not specify a strict format for the components, but rather guidelines on how to effectively structure them to be chainable in a scalable manner. The components themselves and the virtualization approach followed to contain and distribute them can be completely customized and heterogeneous. Moreover, the applications of NFV span across domains, and can be employed in a variety of settings [25].

Software-Defined Networking (SDN) offers a layered-logic way of managing networks [26, 27]. Its core principles are: i) to separate the network control from the network data, ii) to provide a clean interface for interacting with the control, and iii) to provide a central view of the various distributed forwarding elements. This is accomplished by delegating network control decisions to a central service, which has a bird's eye view of the controlled system, and configures its operation in response to policies and events.

Within IoM, the SDN and NFV are used as abstract approaches for organizing software in general, rather than in their literal use in the narrow field of computer networking. The combination of artificial materials, and the extended concepts of NFV and SDN, result in an environment where the wave propagation becomes deterministic and software-driven. We denote such spaces as micro-Managed Energy Environments (mMEEs). Figures 5 and 6 provide an overview of design methodology for mMEEs. Fig. 5 illustrates the envisioned workflow of mMEEs, while Fig. 6 depicts the incorporation scheme of the enabling technologies.

The mMEE design methodology incorporates three core ideas:

1. Express the material wave functions within an NFV framework. Exploit the modularity and chaining ca-

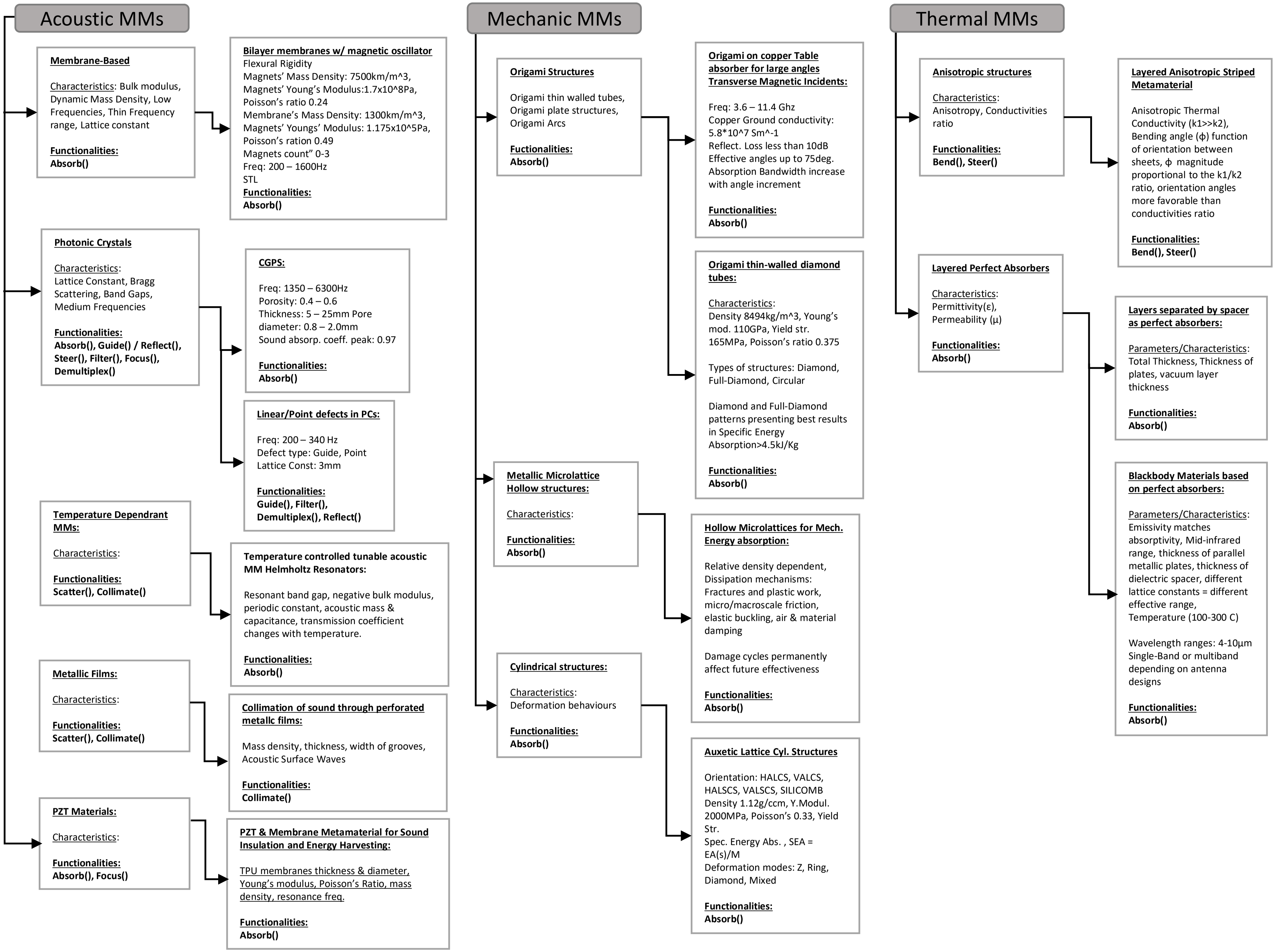


Fig. 3 – Categorization of artificial materials per physical domain, composition and functionalities.

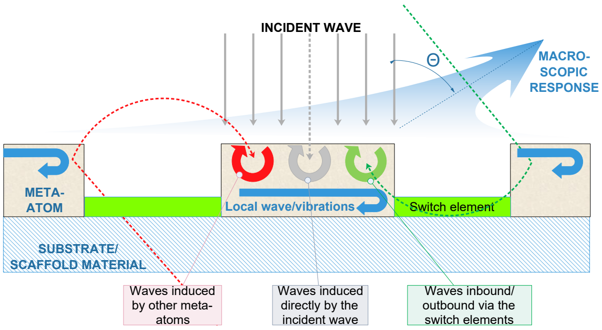


Fig. 4 – The operating principle of artificial materials. Incident waves create a well-defined response to each meta-atom. The individual meta-atom response is altered via switching elements in such a way that their summation (macroscopic response) follows design objective, e.g., wave reflection towards a custom angle Θ.

pabilities of the NFV paradigm, and allow for a well-organized hierarchy of EM functionalities that can be used in a wide application context.

2. Implement the expressed virtual wave functions in an SDN platform. Make use of the centralized control offered by SDN, to obtain the wave propagation requirements within a space. SDN facilitates interfacing with other systems (e.g., localization) and control over the numerous artificial materials within the environment.

3. Employ optimization principles to combine and host multiple virtual wave function instances within an mMEE. Express the wireless device requirements in the form of well-defined optimization objectives, facilitating their “compilation” to matching tile configurations.

A driving principle within the methodology is to make mMEE accessible to a broad developer audience, without requiring expertise in physics, following the paradigm set by the IoM. Therefore, the envisioned hierarchy of artificial material functionalities follows the levels shown in Fig. 5.

At the lowest level, we envisage wave-front manipulation functions, which will allow for custom steering, polarization, absorption and non-linear (e.g., frequency-selective) filtering of waves impinging upon tiles. This basic set of functions will be chained together towards the formation of intermediate-level functionalities. As an example, we propose functions such as `FOCUS` and `FOLLOW`. The former refers to a lens functionality, aimed at gathering ambient energy and directing it towards a given point in a space. For instance, in the electromagnetic domain, this point can be a wireless device for remote charging. The latter makes a function applicable to moving targets. Thus, `FOCUS` and `FOLLOW` could be combined to mitigate path loss for a mobile device within the environment. Additional examples of higher-level functions include `DISPERSE`, for achieving energy dispersion within a space, `BLOCK` (opposite to `AUTHORIZE`), for absorbing wave emissions from unauthorized sources before they propagate within the environment, and `SET_POWER` to define the total power level carried towards a device or a space, e.g., for wireless power transfer tasks.

At the final level, the hierarchy exposes functionality objective templates, which are envisioned as well-defined and parametric optimization goals, organized into four, broad application contexts:

- Communication objectives, which aim to provide advanced QoS to wireless devices, leveraging the mMEE potential, especially in the electromagnetic domain. These examples include bandwidth maximization, bit error rate minimization, extended high-quality wireless coverage and cross-device interference negation.

- Privacy and security objectives, which aim at confining waves within “private paths”, conserving energy and avoiding interference. Moreover, in domains where it makes sense, the same principle can be used for isolating unauthorized or malevolent transmissions within a space.

- Energy exposure objectives, which aim at keeping the exposure of humans and sensitive equipment (e.g., medical) within acceptable levels.

- Power transfer and harvesting objectives, aiming at supplying power to properly equipped devices, or effectively harvesting energy within a space.

An SDN control service is the focal point for mMEE operation. In collaboration with localization and environmental sensing systems, it gathers information on the artificial materials, objects and devices present within a space, their intentions and connectivity capabilities. Subsequently, it expresses these inputs to corresponding objective instances, i.e., a parameterized association between an objective template and a set of wireless emissions.

We envisage environment-wide policies, apart from device-specific objectives. These policies will allow for the expression of:

1. General limits that should be respected within a space with regard to the ambient energy levels. For instance, a maximum allowed value of wireless power throughout the environment in the electromagnetic domain case. We note that this is an additional feature enabled by mMEEs, which cannot be supported by plain environments.

2. mMEE resource reservations, e.g., the “private paths” that should be kept spare as slack reserve, ensuring the proper and timely handling of emergency requests for energy flow micromanagement.

3. Sub-space optimizations, such as offering a specific energy wave micromanagement type within a subspace only.

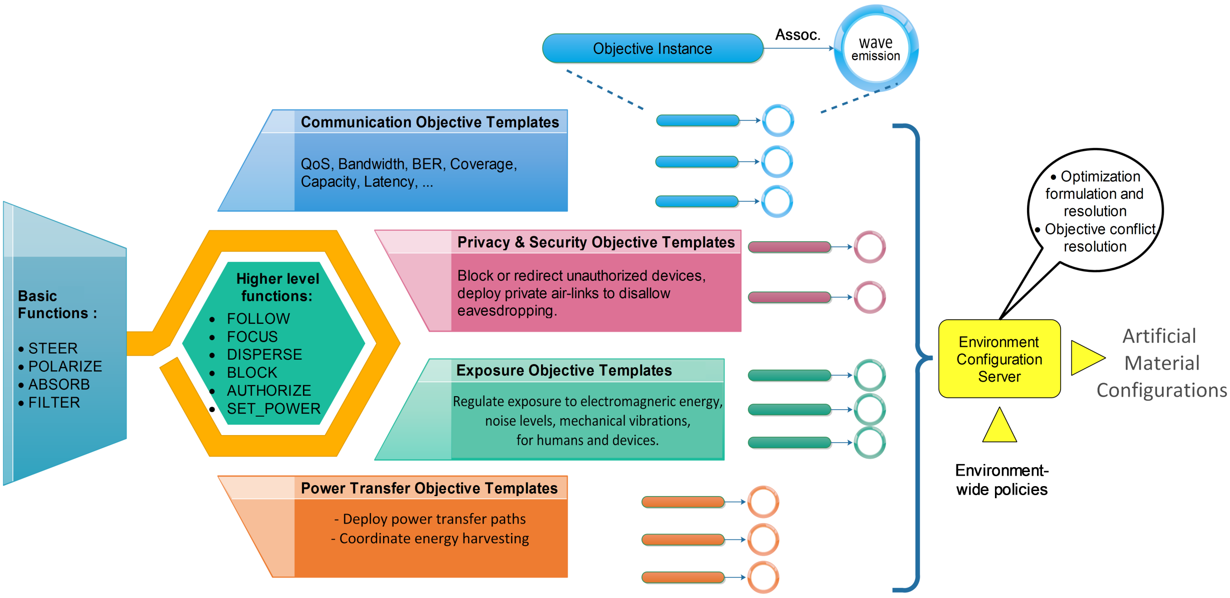


Fig. 5 – Workflow overview of the proposed micromanaged energy environments (mMEEs).

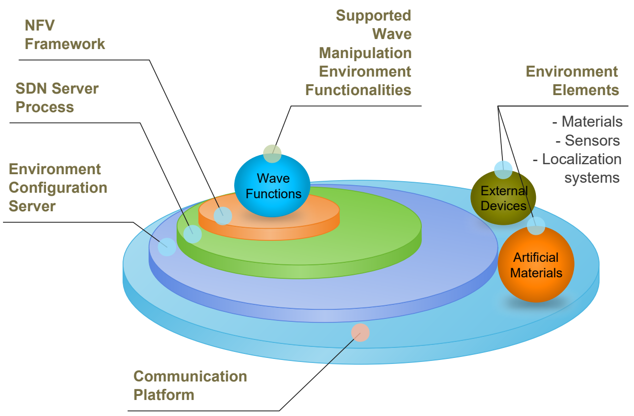


Fig. 6 – Incorporation schematic of the involved enabling technologies, to form micromanaged energy environments.

4. Priorities for the resolution of conflicting operational requirements. For instance, a use case may require power transfer within an area of strict electromagnetic silence. This would means that only acoustic, mechanical and thermal waves should be used for carrying out the power transfer task in this case.

The SDN controller passes the knowledge of: i) the operational requirements of a space with regard to the energy wave propagation control over the wave sources, and ii) the environment policies, to an optimization service. This service deduces the mMEE configuration (i.e., artificial material functions that need to be invoked) that best fit the objectives, subject to the policy restrictions. The SDN controller and the optimization service will be engaged in an online control loop, constantly matching the currently gathered knowledge to the optimal mMEE response.

3. CIRCULAR ECONOMY: GENERAL CONCEPT AND ENABLERS

Circular Economy (CE) is a novel economic thinking which aims to keep physical assets, i.e., products, materials, and components, at their highest utility and value at all times. The main value drivers for a circular economy are extending product use cycle length, increasing product utilization, looping the product through additional use cycles and regeneration of natural capital [28].

The circular economy has its origins in ideas around managing resources, such as the concept of 'Spaceship Earth' by economist Barbara Ward and Kenneth Boulding in the late 1960s [29], and the "limits of growth" thesis by the Club of Rome in the early 1970s [30]. It has evolved from fields like industrial ecology, clean production [31], and waste management [32]. According to Korhonen et al., the most influential concepts for shaping the circular economy were the "cradle-to-cradle" concept of eco-effectiveness [33], and intersystem ecology [34]; both are highly idealized visions, where all natural systems are recoupled into one single system running on 100% renewable energy while recycling all its materials. The first methodic approaches of connecting system inputs and outputs were implemented in the 1990s and 2000s, in the form of initiatives for industrial eco-parks. Circular economy as a term was popularized after 2010 largely through consultancies (e.g., McKinsey [35]), NGOs (e.g., Ellen McArthur Foundation [36]) and international institutions (e.g., World Economic Forum [37]), and attracted the attention of global companies. Contrary to previous concepts such as industrial ecology which were confined to specific (industrial) partners collaborating, a CE's application scope widens, and now spans collaboration between all stakeholders involved in the entire product lifecycle; from then onwards, upstream and downstream supply chain, consumers, businesses, municipalities, governments, NGOs and, arguably society as a whole, become potential actors of the circular economy. In 2015, the Ellen McArthur Foundation and McKinsey presented the butterfly diagram (based on Baumgartner and McDonough's C2C diagram [33]) which depicts how a closed system of production and consumption can be achieved by closing technical and biological loops in various stages of the production process [38]. The key message of the diagram is to maximize product value retention and minimize waste by closing product loops as tight as possible.

In a circular economy, the plethora of stakeholders combined with the different ways to "close the loop" gives rise to new, so-called 'circular' business models, which aim to pair economic with environmental benefits. In the words of Balkenende et al., a circular business model aims to maintain "the highest level of economic value of products, components and materials for as long as possible, while at the same time ensuring that the environmental impact over time is as low as possible" [39]. Herein, new digital technologies play a prominent role as they can introduce visibility and intelligence in products and processes through augmenting them with location, condition and availability properties [40, 41]. Therefore, digital technologies are widely seen as key enablers for circular business models [42], and circular economy in general [43, 44].

The broad usage of the term CE by the scientific community, governmental institutions, policy makers, and businesses has led researchers to attempt to establish a more formal definition of the CE [45, 46, 47]. Although various definitions have emerged, one of the most complete definitions has been proposed by Kirchherr et al., who defines CE as an "economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers" [48]. In order to better understand the definition, and consequently the CE and its wide-ranging implications, we will 'unpack' this definition, inspired by the philosophical 5W1H approach-What, Where, When, Who and How [49] and the proposed CE framework by Nobre and Tavares [50], illustrated in Fig. 7. This allows us the separation of the main question "What is the CE?" which has been answered above, from questions like "Why we should do CE" and "How should we implement CE", thus keeping the definition consistent despite technological and societal changes.

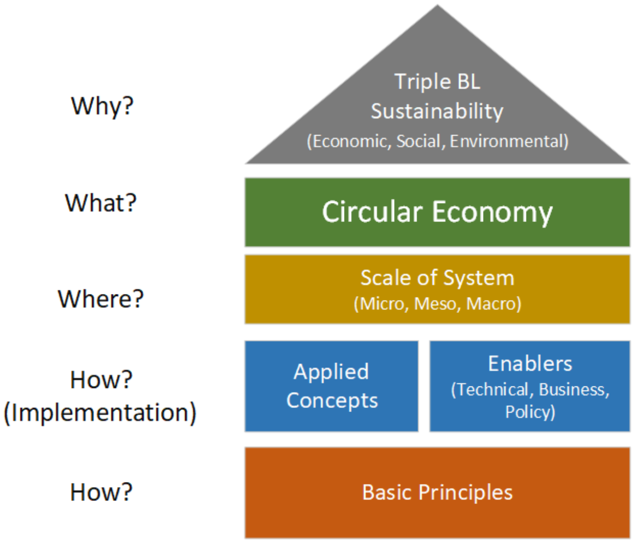


Fig. 7 – Exemplification of Nobre and Tavares' circular economy definition framework (based on [50]).

3.1 Why CE? – Sustainability and the triple bottom line

A series of environmental, social and economic factors have led to an ever-growing need to transition to a more sustainable global society. Serious global environmental challenges such as resource depletion, waste management, water, air and soil pollution, loss of biodiversity, and climate change remain yet unaddressed [51], while at the same time studies predict that 1.7 billion people will join the global middle class by 2030 [37]; thus the growing demands for products will make the necessary resources more contested and scarcer, while further burdening the environment. Simultaneously, social impacts such as poor working conditions, poverty and widening inequality need also to be considered [47]. According to McKinsey research, a circular economy could substantially contribute to minimizing the depletion of resources, reducing waste generation and containing the climate change threat, while simultaneously generating net economic gains of USD 1.8 trillion per year by 2030 [38].

However, the actual environmental benefits offered by a CE have often been debated by scholars. Korhonen et al. define several challenges with respect to environmental sustainability that a CE needs to address, such as constraining the system boundary limits, thus effectively shifting a problem further down the product lifecycle, or creating a rebound effect, where the benefits of increased resource-efficiency are outweighed by unintended consequences leading to more resource usage [34]. Furthermore, sustainable development is made up of three pillars: environmental, economic and social, the latter of which often tends to be underrepresented in the CE debate [52]. These pillars are also known as the triple-bottom line [53, 54], and all of them need to be reflected in CE practices to enable the socio-ecological transition to sustainability [55]. It follows that implementing a CE requires careful analysis, including both the entire product lifecycle and the wider socio-ecological system affected by the product.

3.2 Where to apply CE? – micro, meso, and macro systems

The scale in which a CE is applied is usually classified in three levels: the micro-level, which applies to products, individuals or businesses, the meso-level which includes networks of companies and industrial parks, and finally the macro-level which reflects larger geographical areas such as cities, provinces, regions or countries [56, 57]. Operating at a particular scale significantly affects how a CE is implemented and assessed. Typically, CE business models operate at a firm's micro-level. Moving from a firm-only CE setting to a multi-industry CE scenario or even a nationwide CE policy, inherently will increase the challenges in establishing trust, exchanging information, monitoring progress or making/enforcing decisions [58]; thus the initial, micro-business model will likely be impacted. Likewise, indicators which measure the performance of the CE differ between scales [59].

Examples include: the product-level circularity metric at micro-level, which measures the economic value of recirculated elements divided by the economic value of all elements [60]; the Industrial Symbiosis Indicator (ISI) at the meso-level, which indicates the degree of industrial by-product re-usage to create new products [61]; and Material Flow Analysis (MFA) at the macro-level, which calculates the flow of energy and materials through e.g., a country, balancing inputs (imports and extractions) with outputs (exports, consumptions, waste andaccumulation) [62]. According to Eurostat, MFA indicators can act as proxies for physical or economic efficiency [63]. The previous section has already mentioned the importance of understanding the system boundaries of a CE, in order to know which sustainability pillars are being addressed or impacted. In this context, the micro, meso and macro taxonomy can help to accurately identifying the actors, methods, goals and metrics of a CE approach.

3.3 How to implement the CE? concepts and enablers

Fundamental concepts As mentioned previously, the essence, and arguably the distinguishing feature, of the circular economy is to create closed material loops by design. As a consequence, CE implementation is based on fundamental concepts containing strategies which aim to close these loops in all phases of the product lifecycle. Researchers have summarized these strategies in frameworks, with the 'R' frameworks being the most widespread ones. The most generic framework, 3R, commonly denotes the three strategies 'Reduce', 'Reuse' and 'Recycle' and has its origins in waste management [32]. However, more elaborate frameworks have evolved which more accurately represent the variety of loop closure. Potting's 9R framework is considered one of the most nuanced ones [64]; the Rs are arranged in order of decreasing circularity:

- *'R0 Refuse'* - avoid creation of product by making its function redundant.
- *'R1 Rethink'* - create a product specifically with circularity in mind through targeted design strategies.
- *'R2 Reduce'* - for a producer: to decrease materials, emissions and resources to create and deliver a product; for a consumer: to reduce the product's environmental impact by responsible and efficient use, and making it last longer.
- *'R3 Reuse'* - prolong the functional life of a product and it's parts by transferring ownership to another end user, once the product does not fulfill the needs of the original owner.
- *'R4 Repair'* - bring a product back to its fully working condition; includes also planned repairs (maintenance).
- *'R5 Refurbish'* - further to repairing, to make a used product superior compared to when it was new, by upgrading/replacing parts with technologically more advanced ones.
- *'R6 Remanufacture'* - systematically disassemble, check and a clean product, replacing worn or defect parts usually with used components, or components from recycled materials.
- *'R7 Repurpose'* - use product and/or it's parts in a completely different function than what the product designers intended.
- *'R8 Recycle'* - decompose a product in its constituting materials.
- '*R9 Recover'* - capture the energy contained in waste products through a thermodynamic process or by converting them to biomass.

The strategies are divided in three categories, which roughly map to a product's lifecycle. The first three Rs apply to smart product design and manufacturing (but also efficient product use by the consumer), the next five Rs relate to the extension of the life span of a product and its parts while the product is in use, and the last two Rs concern the useful application of materials during the product post-use phase as well as recovering energy by incinerating the material. The higher the R index, the wider the loop that needs to be "closed", which results in less product value retention and more waste. Conversely, the lower the R index, the greater the impact in terms of resource efficiency.

Applied concepts Derived from the fundamental, theoretical concepts, many applied concepts have emerged which can be introduced to a socioeconomic system to make it more circular. Applied concepts usually differ from fundamental ones due to being more industry or domain specific, although often the boundaries between applied and fundamental concepts are not clearly delineated. Moreover, due to the sizeable and increasing number of applied concepts, they often relate, or overlap with each other. Some indicative examples of applied concepts are listed below:
- *Industrial Symbiosis* is the practice where industries use each other's by-products as inputs to their production process. By-products can refer to materials, but can also be energy, services or facilities [65, 66].
- *Reverse Logistics* refers to managing the reverse flow of goods from the end user back to a manufacturer or other entities which can extract value from it. It entails collecting storing, inspecting and sorting the returned goods, and deciding the best scenario for the next stage of their life [67, 68].
- *Design for X (DfX)* denotes a series of product design strategies aiming to incorporate circularity-enabling properties during its conception [69]. Design targets can focus on e.g., reliability, longevity, resource-efficiency, or on looping the product through further usage by facilitating disassembly, cleaning, remanufacturing, sorting etc. Strategies can include also designing modular, adaptable, compatible and upgradable products, as well as designing for various end-of-life scenarios [70].

Enablers Realizing the CE concepts generally requires a combination of technical [71, 72], business [73] and policy enablers [74]. Many researchers have related the various elements of each category, with the fundamental CE concepts and strategies. Within the context of this study, we present a non-exhaustive list of enabling elements present in each category.

Technical enablers Various technological fields are regarded as CE enablers, such as chemical [75] or thermochemical engineering [76] or biotechnology [77]. Of particular relevance to this paper are digital technologies, which are widely considered of critical importance to the CE [78, 79, 41]. According to Demestichas and Daskalakis, they can be categorized in seven types [80]:

- *Communications technologies* relate to establishing ubiquitous, high-bandwidth, low-latency and resource-efficient information exchange. They encompass the wired and wireless telecommunication infrastructure, communication protocols and techniques, and network management technologies.

- *Computing technologies* refer to cloud, edge, fog, and distributed computing. They include concepts such as virtualization and resource sharing.

- *Cyber-Physical Systems (CPS)* integrate computational capabilities with physical processes. CPS play a key role in smart manufacturing, given that they include technologies such as digital twins, robotics and additive manufacturing, but also in smart farming with e.g., the use of UAV technology [81].

- *Data analysis and artificial intelligence* encompass a wide range of technologies for extracting, processing, presenting and understanding data for decision-support. Notable examples are big data analytics, machine learning, recommender systems and data visualization.

- *Data collection and IoT* comprise of technologies required to capture data from the physical world. Sensor networks, RFID tags, satellite imaging, SCADA, Industrial IoT, Business Information Modelling (BIM) belong to this technology category.

- *Data management and storage* consist of technologies to implement data storage, access and retrieval in a secure, privacy-respecting manner. Apart from established data storage systems such as RDBMS or unstructured databases, blockchains and smart contracts are increasingly finding their way into CE applications [82, 83].

- *Software and simulation technologies* describe the software required to implement CE applications. Important concepts include digital platforms connecting CE stakeholders, or mobile applications for increasing the outreach of CE to end users [84]. Further, simulation models and tools can help analyzing potential CE solutions and optimize them according to CE metrics and Key Performance Indicators (KPIs).

Business enablers Companies rely on business models which reflect both their organizational structure and the process used to create value from their capabilities [85]. For a CE to function, companies need to adapt their business models to include circular strategies, while simultaneously keeping them economically viable. According to research by Nussholz, business models focusing on resource efficiency and resource loop closure can facilitate circular strategies while capitalizing on their associated value [86]. Bocken et al. outline these models in strategies aiming to "slow, narrow and close" resource loops [87]. In CE terminology, "slowing a loop" refers to making more efficient use of resources by extending the lifetime of a product. With respect to the value proposition, circular business models are placed across the entire product-service continuum [88]. At the product end, the lifetime of a circular product can be extended by designing it for longevity, maintainability and repairability; a modular product design can also enhance product reuse, reselling, remanufacturing or cascading, thus further adding value to product ownership; and, materials used can also be chosen so as to allow recycling or safe disposal [89].

At the service end of the product-service continuum lie pure result-oriented services such as using a ride service instead of owning, renting or sharing a car. Companies may also adopt Product-Service-Systems (PSS), located in the middle of the product-service continuum, where a company instead of selling the product offers access to it. Examples are product leasing, renting, or pay-per-use, as well as collaborative consumption models to share a product. Keeping ownership of the product offers incentives to the company to extend product life, and also may facilitate product end-of-life management [90]. Finally, another circular business model is dematerialization, where companies offer digital products where applicable instead of physical ones.

Policy enablers Policy makers have embraced the CE as a means for sustainable economic growth and achieving a series of Sustainable Development Goals (SDGs) set out by the United Nations [91]. Throughout the world, governments are moving towards implementing laws and regulations to facilitate the transition to a CE.

Notable examples are the EU's circular economy Action Plan European [79], which drafts a "regenerative growth model that gives back to the planet more than it takes" while "recognizing the opportunities a CE provides for industry" or China's Circular Economy Promotion Law [65], whose objectives are "economic resilience, resource efficiency and environmental sustainability". This pairing of economic, social and environmental targets creates a fertile ground for policy makers. According to Wasserbauer et al., policy initiatives for a CE can include (1) influencing the product design, (2) influencing manufacturing/provision of products and services, (3) influencing the consumption, (4) addressing waste and end-of-life resource management, and (5) supporting market development of circularly managed resources [92]. Specifically, for the EU's circular economy action plan some of the upcoming policies are:

- *Sustainable product initiative and digital product passports*, which aim to introduce product circularity requirements such as repairability or upgradeability to products. Affected goods will be both at the consumer-end such as electronics, textiles, and high-impact intermediate products such as steel or cement. An accompanying Digital Product Pass will contain information about the product and can be read/updated by all stakeholders throughout the product lifecycle to facilitate activities such as reuse, disassembly or disposal.

- *Green public procurement and consumer law*, which is about providing consumers with better environmental information about products and their life span at their point of sale, as well as repair-manuals and spare-parts for the products. Further, it encompasses developing criteria for procuring environmental-friendly office equipment.

- *Waste framework directive*, which will establish the principle of "Extended Producer Responsibility". This principle will effectively make producers responsible for taking care of products they have introduced to the EU single market once the product has reached its end of life.

4. SYNERGIES BETWEEN ARTIFICIAL MATERIALS AND CIRCULAR ECONOMY

In the following section we present the synergy prospects between artificial materials and the circular economy. We proceed with examining artificial materials through the 9R framework detailed in the previous section. We focus on the implementation aspect, i.e., the *How*, given the practical context of this paper. Specifically:

- *'R0 Refuse'* - artificial materials can potentially make existing, specialized product lines redundant by replacing them with fewer, more generic ones with programmable characteristics.

- *'R1 Rethink'* - with the help of artificial materials, products could be designed in such a way that they could fulfill multiple uses in the product per se. Further, a modular design approach could be taken by allowing the removal of an artificial material from one product and applying it to another product.

- *'R2 Reduce'* - artificial materials can improve the efficiency of usage through tuning their electrical, acoustic, mechanical and thermal properties while in use, allowing the product to adapt to changing environmental conditions. This includes also the concept of harvesting energy from the environment.

- *'R3 Reuse'* - herein artificial materials can offer the dual benefit of increasing a product's attractiveness for reuse by better preserving its condition, and also increasing the product's application scope by modifying the product characteristics through artificial materials by the new end user.

- *'R4 Repair'* - artificial materials can mitigate or eliminate defects in the product's functionality (e.g., induced by wear and tear) by altering the artificial material's properties in the coating of the product.

- *'R5 Refurbish'* - it can be envisaged to replace an artificial material coating in a product with a coating of more advanced artificial materials, offering additional capabilities and increased application scope.

- *'R6 Remanufacture'* - when designed with ease of disassembly in mind, a product's artificial materials can be replaced and reused in other products.

Table 1 – Envisioned synergies between artificial materials and circular economy.

Machine monitoring for precise damage localization and sound filtering	
R2	Minimize inefficiencies in machine operation by keeping machine running in an optimal fashion; decrease waste of resources induced by repair processes.
R3	Increase the possibilities of machine ownership transfer by keeping machine condition at best possible state through constant active learning.
R4	Facilitate and accelerate repairs and maintenance by improved fault localization and targeted repair actions.
R5	Upgrade machinery by replacing original artificial materials with improved ones.
R6	Disassemble original artificial materials in machinery and reuse them in other machinery.
Rapid development of sustainable products	
R1	Simplify design and material composition of products by using generic, sustainable artificial materials in a modular fashion, thus enabling the same product to be adaptable to multiple use cases.
R2	Reduce resource usage during operation. by performing environmental adaptations of the product through tuning of artificial materials within it. Especially important for products to be used in challenging environments.
R3	Modular product design using artificial materials can facilitate product usage in different conditions, hence increasing product reusability.
R4	Repairs can be performed remotely by reprogramming the artificial materials. Especially important for products to be used in challenging environments.
Adaptive acoustics in architecture and civil engineering	
R0	Decrease or even eliminate the use of existing sound-proofing/absorbing/transforming substances by using artificial materials
R2	Increase operational efficiency and resource savings by using artificial materials to optimize sound quality remotely and in real time, in dynamic environments.
Gyroscopic dependent impact absorption in helmets and passenger cabins	
R0	Potentially omit complex and extensive impact-absorbing mechanisms through metamaterial layers and mechanical cloaking
R2	Reduce the overall material needed for impact absorption in existing constructs by including artificial materials providing similar or better performance. Decrease the consumption of medical resources by lowering the frequency and severity of human injuries.
Smart farming	
R2	Reduction of fertilizers and other substances needed to keep crops healthy by using artificial materials to provide optimal environmental conditions for the soil.
R3	Restoration of degraded soil using artificial materials for carbon absorption and temperature regulation.
Common principles	
R7	Create and maintain publicly available databases of artificial materials used in products containing the information required to change their properties, thus enabling experimentation and new usage opportunities for the products.
R8	Allow for easy separation of obsolete artificial materials from product to facilitate recycling of both the product materials and the artificial materials. Leverage properties of artificial materials to facilitate sorting.
R9	Incinerate non-recyclable artificial materials for energy recovery.

- *'R7 Repurpose'* - the possibilities of repurposing a discarded product can be increased by allowing radical programmatic changes to its constituting artificial materials. This can be facilitated by keeping the APIs and knowledge bases of the artificial materials open to the public.
- *'R8 Recycle'* - for the purpose of recycling, artificial materials need to be separatable from the actual product, and they should also be decomposable into recyclable consisting parts. Given the properties of artificial materials, they could also be leveraged to facilitate sorting during the recycling process.
- '*R9 Recover'* - recovering energy from end-of-life artificial materials through incineration is possible, although care should be taken that any harmful substances are removed prior to the process.

Using several exemplary synergy cases, we analyze the benefits in circularity for each, and highlight perspective performance indicators and research challenges. Notice that the proposed synergy naturally touches a vast range of existing industrial systems due to physics-layer/material applicability, with groundbreaking potential in the individual product design and manufacturing level, or horizontally across industrial sectors in the circular economy sense. Here we list such envisioned, exemplary industries, without loss of generality or limitation of applicability, and summarize our findings in Table 1.

Machinery monitoring for precise damage localization and sound filtering A system that can pinpoint irregularities during the work cycles of an engine or any other mechanism that produces particular acoustic fingerprints and consists of moving parts. This can be achieved via an artificial material coating around the motor space, which will actively "listen" and localize specific noises/frequencies that are known that may occur, when specific parts start to wear beyond an acceptable level. The categorization of acceptable/non-acceptable sounds, frequencies and amplitude levels cannot only come from the manufacturer during the production phase of the mechanism /engine, but also by a procedure of active learning and sorting during its use, in the hands of the end user. The concept of predictive maintenance based on the CE principle of *Reduce* applies here, where smart use by the end user minimizes resources during operation. Predictive maintenance further implies product repairability and maintainability, and results in product longevity, thus also demonstrating the CE principles of *Repair* and *Reuse.*

Rapid development of sustainable products Artificial materials can yield: i) product lifetime maximization, and ii) product design cycle minimization. From the lifetime maximization aspect, consider the examples of a house with thermal flaws stemming from suboptimal orientation, or a high precision scientific equipment for challenged environments (e.g., space) shipping with unnoticed design flaws. Both cases would be partially or fully irredeemable with products resulting in low value or a complete lack of usage. In an alternative setting, such products could be repaired even after deployment via proper tuning of the integrated artificial material units within them. Manufacturers could maintain a fast-paced product design, where energy efficiency and sustainability can be upgraded programmatically via software, enabling rapid product development cycles. In this example, the concept of adaptable design is showcased and touches mainly upon the CE principles of *Rethink* and *Reuse*.

Adaptive acoustics in architecture and civil engineering Sound quality and consistency in an auditorium, can be easily affected by multiple parameters such as temperature, population and moving obstacles. In an ideal scenario we would like to be able to control all those possible variables, but this is clearly not always possible. What is possible though is to listen, calculate and overcome the sound inconsistencies in a room by introducing adaptive acoustic metasurfaces, that are able to contribute and deliver a more balanced, normalized and high-fidelity result for the audience in the room. We imagine an auditorium with an altitude range for the audience, having its walls covered with artificial materials. Microphones scattered throughout the room, would take sound samples and feed them to a central control platform, optimizing the room/auditorium/building acoustics in real time. The ability to alter the acoustics with the existing surface has the potential to minimize the amount of specialized sound-transforming materials required to achieve similar results. Moreover, the adaptation of acoustics in real time can contribute to resource savings from operating in a more efficient manner. The CE principles of *Refuse* and *Reduce* apply here respectively.

Gyroscopic-dependent impact absorption in helmets and passenger cabins The combination of mechanical metamaterials with gyroscopic sensitive hardware and tension / stress actuators on the metamaterial layers, can be possibly used to predict the angle, speed and direction of an imminent crash, and re-tune a mechanical cloaking, driving impact vibrations around sensitive areas and maximize safety. The evolution in mechanical metamaterials and their ability to provide adaptive mechanical cloaking can be proven invaluable for helmets and passenger cabins for various fields, providing a reliable assistance in addition to already existing technologies. The additional protection provided can be crucial in minimizing the effect of injuries, thus lessening the strain on medical systems and related resources consumed (CE principle: *Reduce*). Moreover, advanced, artificial material-based impact protection systems could potentially to eliminate existing resource-intensive mechanisms of providing protection (CE principle: *Reuse*).

Smart farming: Soil catalyst thermal routing blanket for fostering micro-organisms reproduction and land fertility To tackle the problem of flora elimination, soil degradation and the difficulties farmers face with crops due to extreme weather conditions and overly-exploited land, a thermal blanket that also acts as a catalyst for carbon absorption and actively reroutes temperature away from or towards the crops area in the morning and late at night, can bring some hope for temperature, humidity and carbon deposits manipulation and creating an environment for organic matter to thrive again, even in places that have faced extreme degradation. Making sure the soil that the plants grow in is manageable and "live-able", and possibly unlocking the potential for soil restoration and some new kinds of crops to thrive in different lands. From a CE vantage point, soil catalyst thermal routing does not only enable the reuse of soil, but can also potentially contribute to the reduction of fertilizers and other substances which may burden the environment, thus reflecting both the principles of *Reuse* and *Reduce* respectively.

Additionally, we mention the following affected sectors and their additional prospects:

Medical imaging, multimedia and acoustics market. Artificial materials can act as environment-adapting absorbers of EM and acoustic energy. This empowers them to operate as noise cancelling devices, with an extremely high number of applications in medical imaging (MRI) and transplants. Image accuracy is crucial for correct diagnosis as well as image post-processing tasks [93], therefore benefiting the efficiency of provided healthcare services and the resource-conserving operation of medical devices.

Wireless communications and radar market, and especially in the form of intelligent surfaces [5], due to their potential to be used in highly efficient, low-power MIMO antenna arrays with programmable directivity in 5G and beyond.

Civil engineering market. The interconnectivity potential of the IoM, coupled with the programmatic manipulation of sound, heat and electromagnetic energy can offer novel abilities to smart buildings, such as environment-adaptive thermal behaviour, selective sound insulation, adaptive wireless coverage in an indoor space, minimization or nullification of ambient electromagnetic radiation, enhanced and cost-effective resistance to vibrations and earthquakes. Especially when integrated in Building Information Modelling (BIM), a digital model of the building consisting of its physical and functional characteristics [94], IoM-induced activity can contribute to real-time energy management and structural adaptions.

4.1 Discussion: Performance metrics for the artificial materials/circular economy synergy

Along with interventions to make a product more circular using artificial materials, it should also be considered how their impact on circularity can be measured. Assessing the performance of a CE is an ongoing topic; the systemic, multidisciplinary nature of the CE, its multiple strategies to slow down, or close resource loops, its different scale of applicability (micro, meso, macro) combined with the three sustainability dimensions (environmental, economical, social), have resulted in over 60 proposed metrics and KPIs [95, 96, 97]. From an artificial materials perspective we direct our attention to micro-level metrics, given their product-centric nature. Kristensen and Mosgard analyzed 30 micro-level metrics and grouped them into nine categories: recycling, remanufacturing, reuse, disassembly, lifetime extension, resource-efficiency, waste management, end-of-life management, and multidimensional indicators [98].

Recycling metrics emphasize the amount or value of material that can be recovered from a product. They are commonly expressed in ratios or percentages of the recovered material relative to the total material of the product. Therefore, to avoid a negative impact on these metrics, artificial materials need either to be recyclable at a similar (or better) rate compared with the overall product, or should be removed prior to recycling.

Remanufacturing metrics measure the circularity induced by remanufacturing, refurbishment and repurposing a product. They aim to convey how much economic and environmental benefit is gained by performing the aforementioned activities on a product, taking into account various factors such as cost of the process, eco-costs and projected market value of refurbished products. Herein, the potential exists to increase the projected market value of a remanufactured or refurbished product by retrofitting it with artificial materials. However, the required costs and environmental impact to do so need to be low enough to justify the effort and increase the metric with respect to not using artificial materials.

Although reuse is considered an important CE strategy, there are very few *reuse metrics* due to the difficulty of measuring how often a product is used again by the same or other users. However, one of the metrics in this category, the Sustainability Indicators for CE (SICE) metric also includes the product's reconfiguration potential, and its ability to satisfy multiple functionalities [99]. A product augmented with artificial materials can therefore score higher on this metric than a conventional product due to its ability to change its characteristics.

Disassembly metrics relate to the time, cost and complexity required to take a product apart. Ease of disassembly is a prerequisite for many CE strategies, most notably *Repair*, *Refurbish* and *Remanufacture*. These metrics consider also the sequence of disassembly, the handling of the product due to structure and geometry, and the necessary tools for performing the task. Products coated with artificial materials may be disadvantaged compared to their conventional counterparts since they include more parts; it thus follows that these kinds of products should be designed in such a manner that the coating poses as little overhead to the disassembly process as possible.

Lifetime extension metrics address the longevity of the products and materials. They measure the units of time that a product or material is retained within the system, including also the time following product refurbishment and product recycling. Few lifetime extension metrics exist, partly because of the difficulty to know ex ante about the product and market conditions during its foreseen lifetime, and partly because product lifetime extension is covered implicitly by other metrics, e.g., remanufacturing or recycling. Products with artificial materials possess the qualities to excel in these metrics, given their intrinsic capability to mitigate defects and adapt to environmental conditions during operation.

Resource-efficiency metrics examine the quantity of resources that a product requires in relation to the value it provides. Fewer consumed resources during the product lifecycle will usually result in a higher resource-efficiency score. Similar to the disassembly metrics, products coated with artificial materials may be disadvantaged with respect to their conventional counterparts because of the additional parts and resources needed to create/assemble them. However, artificial material coated products could require fewer resources during product operation, thus pairing resource losses and improving the metric.

Waste-management metrics for products at a micro-level rely on material flow calculations to determine the ratio of non-recyclable materials to the total materials used. Non-recyclable materials are considered waste. For a product augmented with artificial materials, or products where artificial materials replace conventional materials, it is essential that the artificial materials do not end up as additional waste, thus resulting in a lower waste management score compared to conventional products.

The last two categories can be considered as a superset of metrics and strategies presented in the aforementioned first seven categories; *end-of-life management metrics* compare the circularity of various product EOL scenarios, while *multidimensional indicators* combine metrics from multiple categories to yield an overall circularity score. From analyzing the various categories of metrics, we believe that products consisting of artificial materials need to be benchmarked against their conventional counterparts with respect to their circular performance, to accurately determine whether and where advantages exist. Especially in the categories of *Remanufacturing metrics*, *Reuse metrics* and *Lifetime extension metrics*, the application of artificial materials can lead to measurable circularity performance improvements. Nevertheless, the artificial materials injected into products still count as additional resources in material flow calculations, and therefore need to be managed carefully regarding disassembly and recycling in order to avoid reversing circularity gains.

5. CONCLUSION

The present paper studies the use of intelligent, artificial materials as enforcers of circular economy principles in the lifecycle of products. The study exploits the fact that intelligent materials can change the electromagnetic, mechanical or acoustic properties following software directives. These artificial materials can be incorporated within products, objects and spaces and micromanage electrical and mechanical energy. Thus, they can mitigate on-the-fly the ecologic discrepancies of the original product design. The study presented a methodology for organizing, controlling and orchestrating intelligent materials, while discussing their potential in circular economics.

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