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# MGE2: A framework for cradle-to-cradle design

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**Abstract**
Design and ecology are critical issues in the industrial sector. Products are subject to constant review and optimization for survival in the market, and limited by their impact on the planet. Decisions about a new product affect its life cycle, consumers, and especially the environment. In order to achieve quality solutions, eco-effectiveness must be considered, therefore, in the design of a process, its product development and associated system. An orderly methodology is essential to help towards creating products that meet both user needs and current environmental requirements, under paradigms that create environmental value. To date, the industry has developed techniques in an attempt to address these expectations under Cradle-to-Cradle (C2C), which is loosely structured around the conceptual frameworks and design techniques. The present work describes a new framework that encompasses all stages of design, and enables interaction under a set of principles developed for C2C. Under this innovative new paradigm emerges the Genomic Model of Eco-innovation and Eco-design, proposed as a methodology for designing products that meet individual and collective needs, and which enables the design of eco-friendly products, by integrating them into the framework of the ISO standards of Life Cycle Assessment (LCA), eco-design, eco-labeling, and C2C certification.

*Keywords*: Eco-design, Sustainability, Industrial Ecology, Life Cycle Assessment, Eco-effectiveness, Eco-innovation

# MGE2: Un marco de referencia para el diseño de la cuna a la cuna

**Resumen**
El diseño y la ecología son temas cruciales en el sector industrial. Los productos están sometidos a revisiones constantes para sobrevivir en el mercado y a optimizaciones que los mantienen bajo los límites de impacto sobre el planeta. Las decisiones acerca de un nuevo producto afectan su ciclo de vida, los consumidores, y sobre todo el medio ambiente. Con el fin de lograr soluciones de calidad, Eco -eficacia debe considerarse, por lo tanto, en el diseño de un proceso, su desarrollo de productos y el sistema asociado. Una metodología ordenada es esencial para ayudar a la creación de productos que satisfagan tanto las necesidades de los usuarios y los requisitos medioambientales actuales, bajo los paradigmas que crean valor ambiental. Hasta la fecha, la industria ha desarrollado técnicas en un intento de abordar estas expectativas bajo la cuna a la cuna (C2C), que está vagamente estructurada alrededor de los marcos conceptuales y técnicas de diseño. El presente trabajo describe un nuevo marco que abarca todas las etapas de diseño, y permite la interacción bajo un conjunto de principios desarrollados por C2C. En virtud de este nuevo e innovador paradigma surge el Modelo de Genómica de Eco-innovación y el diseño ecológico, propuesto como una metodología para el diseño de productos que satisfagan las necesidades individuales y colectivas, y que permite el diseño de productos respetuosos del medio ambiente, mediante su integración en el marco de las normas ISO de Análisis de Ciclo de vida (ACV), el ecodiseño, ecoetiquetado y la certificación C2C.

*Palabras clave*: Ecodiseño, Sostenibilidad, Ecología Industrial, Análisis de ciclo de vida, Eco-efectividad, Eco-innovación.

## 1. Introduction

*To meet present needs without compromising the ability of future generations to meet their needs* is the most widely used definition of sustainability. This concept has become highly relevant, now recognised as the basis of industrial, business, economic, governmental or social activity. Sustainability is built on three vectors that define and develop

"3E" sustainable strategy: Economy, Equity and Ecology [1]. Over recent decades, these vectors have occupied various positions, both while being aimed at reaching their full interaction, and in industrial activities considered to be sustainable. These dimensions or vectors of sustainability are deployed sequentially in order to attain business goals, forming a pyramid whose economic base needed guaranteeing before taking into account any social and ecological criteria. Through innovation and constant attempts and proposals for change towards sustainable development [2], the industry has built various frameworks (paradigms in the design), all based on a group of principles, techniques and tools, among which the most significant are Natural Capitalism, the Natural Step, Cradle-to-Cradle (C2C), and Permaculture. These approaches all lay out a new distribution of the three vectors of 3E sustainability, arranged at the vertices of a triangular mesh where sustainability is addressed equally from any point of view. By taking the innovative cradle-to-cradle (C2C) paradigm [3] as the origin, and by considering it as the most significant framework for the advancement of sustainability in the context of engineering projects in view of its operational and eco-systematic character, this paper presents a new model of design and development of industrial products (MGE2). Our principal goal is the realization of theoretical contributions, by establishing the foundations and principles of bio-inspired C2C; followed by our goal to develop a specific and practical methodological proposal of bionic design which can be supported by Concurrent Engineering and PLM (Product Life Management) environments [4], whilst taking into account a continuous review based on Life-Cycle Assessment. In this proposal, new ideas of the C2C perspective are coordinated, thereby constituting a way to implement the basic principles of this new paradigm, which reflect the lessons learned from the eco-efficiency and eco-innovation approaches. In this new perspective of eco-efficiency, the model can support all the ISO standards requirements introduced to date, it can extend the range of solutions in order to improve the performance of impact minimization, and it can help to resolve, through the design of sustainable products, the environmental problem that current industry is causing on the planet.

## 2. Material

Sustainable design involves a strategy that encompasses technological, economic, cultural, social, technical-productive, aesthetic, and environmental factors. The consideration of this set of issues within design implies that those industrial organizations that carry out eco-design projects obtain a set of benefits as a consequence of the introduction of an innovative factor in their business policy.

To date, design for sustainability and environmental management in industry have evolved into the following stages:

a) Reactivity: Knowledge and reaction. Mass production in industry has marked the future of the planet through its high consumption of resources and excessive pollution. Faced with this situation, and with the alarm raised by experts and environmental groups, governments began to take measures and to demand certain actions from heads of industry. Society began to become aware of the problem.
b) Gate to Gate: End-of-pipe technologies (1). After this first period of awareness, public administration introduced the first legislation that demanded pollution control, for which they began to implement the End-of-pipe technologies, based on pollution-control (once it is triggered) at the end of the production line. This involved an additional demand for energy, materials and specialized equipment.
c) Cradle to Gate: Optimization (2). The eco-efficiency idea was extended when the industry realized that the optimization of activities and processes was the next best option. To this end, the vision of preventing pollution rather than fighting it was incorporated, and focused mainly on the manufacturing phase and on the reduction of raw materials.
d) Cradle to Grave: Eco-efficiency (3). A step beyond optimization, the idea of eco-efficiency as a basis for industrial strategy was expanded, and was developed not only in the manufacturing phase, but also to cover all stages of the life cycle, from the extraction of materials to the end of the life of products. This involved comprehensive supervision and action in all stages of the life cycle of the product based on ISO 14000 standards, the implementation of legislation and BREFs, Best Available Techniques and optimization of technologies, in order to improve the control process and pollution prevention.

Cradle to Cradle: Eco-effectiveness (4). As the latest advance, the C2C perspective is under development. Its aim is not only to ensure the efficiency of processes throughout the life-cycle stages, but also involves a thorough study of material flow, essential for the end of the useful life of products, since they can be reused or recycled (without entailing reduced quality). This would eliminate the current system of waste landfill or pollution of the atmosphere by means of the many existing recovery systems.

The first noteworthy mention of C2C was with the publication of *"Cradle to Cradle: redesigning the way we do things,"* written by Michael Braungart and William

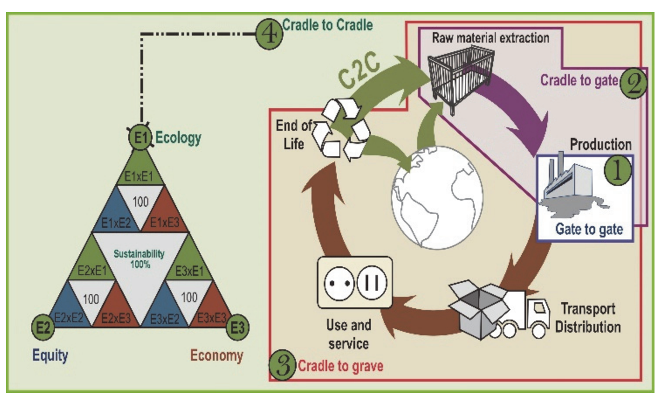


Figure 1. Evolution of the life cycle of products towards sustainability; Source: The authors

McDonough [1], which introduced the first foundations of a new paradigm for ecological industry. The authors considered this innovative perspective as the start of the "next industrial revolution." Thanks to the consideration of the design of products and systems under the perspective of sustainability during their whole life cycle, an architecture is conceived of the product and associated systems (manufacturing processes, use and disposal), seamlessly integrated with the flows of matter and energy of the natural ecosystem (naturesphere) and technical ecosystem (technosphere). The three aforementioned dimensions of sustainability are available through C2C, simultaneously articulated and under a fractal design [1]. Sustainability is placed in a triangular domain where none of the three concepts (economy, ecology, equity) is trivial, since all three are considered as equal in size, value and interest, thereby constituting the sustainable methodology of welfare economics. When tackling the design of a new product, each vertex of the fractal triangle and the interaction of each concept with the other two vertices are taken into account, without forgetting any of the qualities that will fully satisfy (thanks to the product) the overall needs that society demands (present or future), the environment, or project viability. This approach eliminates the following situations of unsustainability:

1) An economic and financial capital outlook, suitable only for product profit (capitalism): based exclusively on profits without considering environmental and social aspects.
2) A vision of equity and of social capital, with attention paid to the market sectors of disadvantaged groups and to cultural sustainability. This approach fails to consider both economic and environmental aspects.
3) An ecological and natural capital perspective for the sustainable integration of the product into the environment without considering social and economic criteria.

This new strand of research is currently under development, with high expectations of its full implementation in the future, whereby it will set a new paradigm for design, and will develop products and industrial systems based on the search for eco-efficient solutions (quality) with a closed life cycle. This situation is supported by the European project *Cradle to Cradle Network* (C2CN) [23], approved in February 2010 for the development of the C2C paradigm and its distribution in Europe, within the INTERREG IVG (Innovation and Environment Regions of Europe Sharing Solutions). The C2C framework is insufficiently developed for the further incorporation into the product design requirements that the products can also be regenerated at the end of their useful life, and that they generate environmental value within their life cycle. This determines the need for the design and development of products, which, in addition to conceiving sustainability in a systemic manner, also integrate life-cycle analysis (LCA), cleaner production and industrial ecology, and eco-efficiency and eco-effectiveness [5], all within the framework of Best Available Techniques. To this end, we propose and develop the “Genomic Model of Eco-Innovation and Eco-design, MGE2.” This is a new process for the design and development of products that converts C2C into a practical and applicable technique.

## 3. Methodology

### 3.1. *Cradle to Cradle - C2C*

The core of the C2C paradigm [1] consists of eco-innovative design solutions inspired by nature, in their closed cycles of materials and eco-efficient industrial metabolism (in the absence of xenobiotic substances). The objective is to incorporate eco-efficient solutions that add value in order to help minimize the use of natural resources, by placing value on resources manufactured in successive cycles, which involve a parallel reduction of environmental degradation. To this end, the methodology must be designed in such a way that nature is seen as: a model (through imitation of forms, processes, flows, interactions and systems); units of measure (via comparison of designs with natural references and verification of whether the solutions are as effective, efficient, simple, and sustainable as those found in nature); and mentor (through the acceptance that human activity and industrial practice is part of nature, and acting accordingly). Approaches that arise in relation to the concept of eco-effectiveness in C2C [26], provide the search for quality solutions, by doing “more with less” without slowing down the environmental problem (which does not just minimize resource consumption, emissions and waste, but actually eliminates them), all according to the concept of Biomimicry, otherwise known as Innovation inspired by nature [6].The authors of this idea [3] propose a series of ideas that we have organized into nine practical principles, (Pi), which ensure products are obtained that incorporate closed loops, no waste generation, and recovery of all materials without any loss of quality, thereby keeping the natural capital of the planet in line with the character of a system that is open in energy and closed in materials.

P1. Proactive refocus (positive impacts). As opposed to the reactive approach of environmentalists to "reduce, reutilize and reuse" that only slows down degradation without resolving the problem, this principle proposes proactive action before the generation of impacts. It rejects the assumption that the industry must inevitably destroy the environment, and it recognizes the potential for innovation, ingenuity, creativity and prudence, and imagines systems which purify water, air and soil, thereby helping to regenerate the environmental value lost in recent decades.

P2. Systemic and integrated conception of product metabolism (systemic approach). This principle includes a systemic perspective of the lifecycle of products by introducing closed metabolic processes for technical and biological nutrients of the naturesphere and technosphere. This setup of closed cycles converts the output into input (waste = food).

P3. Fractalization of sustainability (eco-innovation). The 3E strategy transforms the problem-resolution process and obtains solutions based on opportunities of values with a triple calculation of results (economic, social, and ecological).

**P4. Bio-inspired eco-innovation (biomimicry).** The search for quality solutions based on effective bio-inspired innovations[6]. This will rule out ineffective solutions (such as continuous optimization which minimizes but fails to eliminate the problem of eco-efficiency), by endowing products and industrial systems with added environmental value, and by helping reduce the use of natural resources and reduce environmental degradation, which directly or indirectly contributes towards the minimization of environmental impact.

**P5. The product as a living being and its system, associated as an ecosystem (environmentally friendly).** Products are considered and developed as the metaphor of a living being with its complex relationships with the environment, whose metabolic flows of biological and technical nutrients are included within closed cycles without any loss of value and without damage to the environment.

**P6. Eco-intelligence (maximization of the natural value)**. Ecological intelligence is the concept that describes the ability to design and develop sustainable products or services. From the initial conception of the design, the carrying capacity of the ecosystems associated to its life cycle is considered, and hence the network of interactions is rendered environmentally friendly and beneficial to the environment and the agents involved. In this way, the lost environmental value on the planet can be regenerated.

**P7. Respect for and promotion of diversity (resilient design)** Diversity (genes, organisms, populations, ecosystems) promotes resilience and robustness of the product and associated systems, thereby ensuring security in a changing world. Therefore, the variety belonging to the natural environment, and that of the technosphere, which is influenced by the manufacture, use and disposal of products, should not be adversely affected. This implies respecting and enhancing natural and technical diversity, and the avoidance of xenobiotic products and substances [27].

**P8. Eco-effectiveness versus eco-efficiency (quality solutions).** Eco-effectiveness is associated with quality solutions and directly addresses the concept of maintaining (or improving) the quality of resources and productivity through closed cycles. Rather than eliminating waste, we advocate a cyclic metabolism or a complete closure of material cycles (refuse is non existent) where waste of one system becomes a nutrient for other systems. This idea is taken from nature, where there is no waste and therefore all technical or biological cycles are closed (waste = nutrient).

**P9. Use of renewable energy (Exergy approach).** The energy to sustain the metabolism of the food chains of biologicaland technical nutrients should preferably be obtained from renewable sources, rather than through the exploitation of resources that provide energy from fossil fuels, which, for millennia, has devastated the areas where these materials have been processed [28].

### *3.2. Material Flow Analysis (MFA) and Substance Flow Analysis (SFA)*

The paragraphs above state that the design of a product within the C2C context must deal with the concept of closed flows of materials and substances. This implies including an eco-systemic perspective in the design and development process where we will define new rules that convert waste materials into nutrients, in such a way that they are allowed to flow within two metabolic cycles, as shown in Fig. 2 (the biological cycle, associated with the naturesphere, and the technical cycle, associated with the technosphere). This is made possible thanks to MFA (material flow analysis) and SFA (substance flow analysis) with which we can simulate the principle of conservation of matter carried out by nature, where the flow of material, substance and energy is constant [7]. With these two methods, all flows within the life cycle of the product can be taken into account through Material Flow Accounting, (MFA). Interest in these two types of analyses due to their different trophic levels and to their associated energy, appears the moment when the aim becomes that of converting the flows generated by the industry into the metaphor of the trophic chain which is followed by natural ecosystems. To this end, materials must coexist exclusively in the two metabolic routes to achieve the closed nature of the cycles of flows (hence the name, from cradle to cradle). This eliminates the concept of waste, and renewable energy resources are chosen for the metabolic reactions. Within the C2C design, the following types of metabolism associated with the product have been established:

**Metabolism associated to Naturesphere.** These are a result of processes linked to biological nutrients or biodegradable materials that could be metabolized and regenerated by nature. In this cycle, the material may return to the biosphere (lithosphere, hydrosphere and atmosphere) only as organic material (neither synthetic nor toxic). Discarding a chair made entirely from wood is one example. This metabolism is represented in Fig. 2, BN.

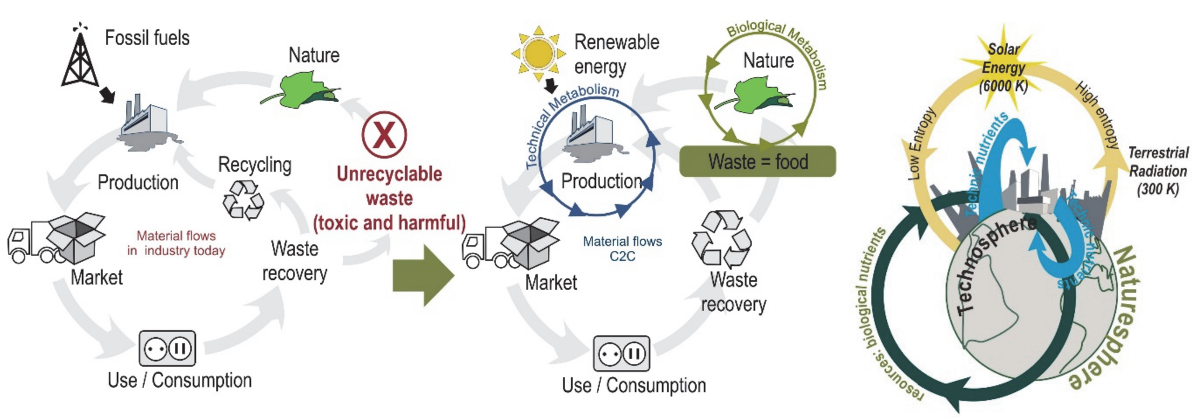


Figure 2 Cyclical Metabolisms in C2C (adapted from [17,21,24])

a. **Metabolism associated to the Technosphere.** This consists of technical materials and processes related with product life cycle, forming the set of technical nutrients to be metabolized by the Technosphere (in Fig. 2, TN), divided into: B1- Downcycling is the path where the materials lose quality and value. With use, their elimination or disposal is only postponed, and their destructive cycle is extended, for example, the manufacture of sheets for thermoformed, plastic lumber, pallets or thermal fillers from PET (polyethylene terephthalate) bottles. These having fulfilled their initial goal are incorporated into a process where they suffer a loss of certain properties, and can be exploited if they are used in the manufacture of only those products that do not require the features offered by the primary material. And B2 - Upcycling transforms the unused material or product, otherwise destined to become waste, into another material or product of equal or greater utility or value. These paths lead to materials of greater value, through being transformed into preferential materials in the eco-design of products and industrial ecology. An example can be found in the car industry [8], where once each vehicle becomes obsolete, many engine parts could easily be reused in other applications. Both the MFA and the SFA are carried out through the study of flow diagrams, material balance, and simulation processes of the values of environmental impact [9]. Their use enables us to also understand the metabolic flows described above and the energy inherent in the processes, the toxic substances and their flows within every phase of the life cycle (extraction, manufacturing, use, withdrawal, and end of life), currently included in the field of study of ecotoxicity.

Clearly, the purpose of the design with C2C is to improve flows associated with the product in relation to the metabolic capacity of the planet: the Naturesphere and Technosphere. The C2C paradigm also describes the need to improve the metabolism of the Technosphere, through the implementation of industrial ecology systems within which the effective management of nutrients is carried out. Sets of intelligent materials are formed that enable upcycling, thereby leaving downcycling as obsolete, depending on the technology available and the development of new materials. For the preservation of metabolic routes in closed loop cycles, maintenance from energy flows is needed, which in turn requires a surplus of resource consumption and pollution generation for their production. In order to minimize this impact, the replacement of fossil fuels by renewable energy sources has become a priority.

### *3.3. Industrial ecology and cleaner production*

There are three types of industrial systems [10], which co-exist today. Type I is the conventional and unsustainable system that was born in the industrial revolution and is about to become extinct. Those companies and organizations that have begun to become aware of sustainable development and environmental care are matched to type II. Finally, type III is not still considered by many systems (although some are running currently, such as the Eco-industrial Park in Kalundborg, or are under development, such as the Eco-industrial Park in Dallas Texas). There are many studies and research projects about industrial ecology's dynamic and models through which projects are being proposed to create industrial ecosystems and eco-industrial parks. Adopting this system with its characteristics offers companies the ability to minimize the environment impact and reduce production costs through an energy and resources efficiency plan. Its application prevents contamination, allows resource recovery and reconstruction of damaged resources in degraded ecosystems. Industrial ecosystems are a powerful economic tool, both for industry and close communities that may achieve benefit from park's clean management .

This has been made possible thanks to MGE2, which guides planning and productive industrial activity in order to achieve sustainability in manufacturing processes. MGE2 allows industrial plants to manage inflows and outflows efficiently. Good planning will optimize the manufacturing phase where industrial system quality will be strengthened.

### 3.4. Application Tools

The C2C paradigm and framework have developed a set of techniques and individual tools, which have yet to be integrated into a model of product design and development. From among other survey techniques, possible applications could be found for biodegradable materials, analysis and assessment of material flows (MFA), substance flow analysis (SFA) [25], life cycle analysis (LCA), Sankey diagrams of energy balances, a study of biological and technical metabolic routes, the design of a closed nutrient cycle, exergy analysis, design and development of metabolisms of the product, product disassembly trees, chemical design, triple E strategy (or fractal pyramid), X-list, gray-list, P-list, eco-effectiveness, the rediscovery of environmental concepts, the five stages of redesign (no use of harmful pollutants, monitoring reports, positive passive list, active positive active list, and rediscovery or innovation), and bio-inspired design [11]. The stages of product design and development are complex, non-intuitive, and fail to guarantee good environmental performance, all due to this situation of isolated techniques with no specific establishment for the way in which they should be applied. Based on C2C, a new design model (MGE2) is proposed in order to integrate paradigm principles and techniques in the design and development process.

### *3.5. Genomic Model of Eco-innovation and Eco-design - MGE2.*

The aim of the proposal for the genomic model of design and development is to integrate the C2C paradigm, the material and substance flow analyses together with all aspects present in the analysis of the life cycle of products. To this end and through the achievement of a flow of adequate nutrients (simulating the trophic chains that living beings follow in their ecosystems), the objective is the incorporation into the products of a series of characteristics that designate their sustainability during manufacture and use, and at the end of their useful life, where they repeatedly restart the process as technical nutrients, thereby rendering them autopoietic [12], and self-healing.. The design requirements that MGE2 incorporates into products are defined in order to ensure eco-compatibility, by enabling integration of the nutrients into successive redesigns (new generations of products), while taking into account the evolution of the associated ecosystem product (market, Technosphere, Naturesphere, etc). The model reflects the requirements of complexity and flexibility of the new environments of the development known as PLM - Product Life Management [4], and is configurable in response to the complexity of the product, thereby forming an open reference architecture for concurrent, collaborative, and distributed engineering environments. Bearing these aspects in mind, the following dimensions are proposed for the characterization of the products:

Static dimension, which incorporates a sustainable character into the product (self-compatible) defined as:

- Autopoietic (self-regenerating): the product regenerates itself.
- Environmentally friendly: the different solutions are designed based on the capacity of the receiving environment.
- Metabolizable: the flows of substances and materials are designed in response to biological and technical metabolic processes.
- Systemic (holistic): different projective scenarios, cyclic interactions of the product, and metabolic flows generated in its life cycle are all studied, for both biological and technical nutrients.

Dynamic dimension, which determines the variations in the different generations of products, endowing them with an evolutionary character (resilient and robust), differentiated by:

- Natural selection (environmental pressure): resulting from the interaction of the genome (internal characteristics of the product) with the environment (which selects the best adapted) leading to the phenotype. This constitutes the learning factor between generations of the product.
- Recombination and mutation (the combination of two different genotypes): both correspond to the random processes of genetic transmission between generations and to strategies of hybridization between products in the company's portfolio.

In order to correctly analyse and synthesize these dimensions of the sustainable product with the appropriate connotations, a series of steps is defined that guide the whole design and development process and which render the product sustainable.

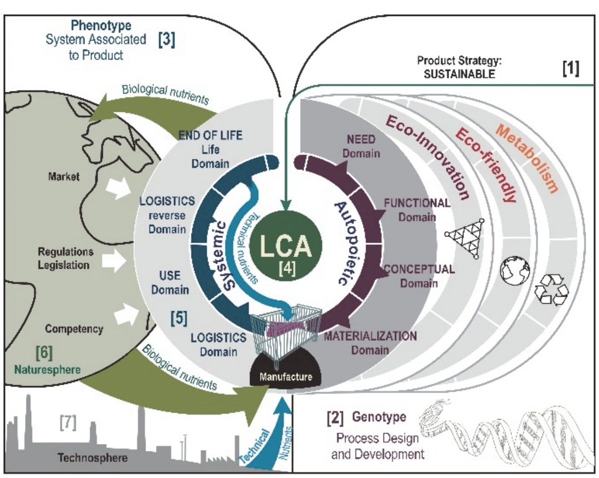

Figure 3 The Genomic Model of eco-innovation and eco-design; Source: The authors

Taking the states and evolution of natural systems as a reference, the process is divided into two sections: genotype, the stage of gestation of the product (design and development); and phenotype, which defines the associated system of the product (manufacturing, use, withdrawal and end of life, market, policy, legislation, and competence). The terms "genotype" and "phenotype" are characteristic of genetics, where the duality of organisms is represented. These have been chosen as an analogy to describe the internal characteristics of a product, or its "genes" (genotype) and its expression or interaction in a certain environment or "ecosystem" (phenotype). The two processes (genotype and phenotype) need a strategy (sustainable) that determines their evolution, and require constant analysis and interaction management, achieved with a Life-Cycle Analysis [13]. Hence the MGE2 has a five-fold structure:

<MGE2>=
<<ProductStrategy><Genotype><FoodChain><Phenotype>
<LifeCycle Analysis>>

< Product Strategy > (1) In this stage, the objectives are defined under C2C principles, which design or redesign a new product and manage its life cycle. These aims establish the product strategy of a systemic, autopoietic, eco-innovative, eco-friendly, and metabolizable character.

<Genotype> (2) Based on product strategy, various techniques and design tools associated with C2C are applied in order to establish the "genes" that define the materials (nutrients), metabolic routes, and the types of energy (possibly renewable) which will sustain the products from cradle to cradle. The genomic design of the product establishes the domains of needs, functions and concepts, and materialization. In these domains there is a series of techniques to ensure eco-innovation, eco-compatibility and metabolism [14]. The main tool for the assessment of design solutions that establish these "genes" consists of the basic strategies of eco-design, supported by biomimetic design strategies oriented towards eco-effectiveness, all with the intention of obtaining the closed-loop cycle characteristics of the C2C perspective which are to be applied in each domain (view Fig. 5).

<Food Chain> (3) After defining the "genes" that characterize the product, the product begins its phase of growth and development, that is to say that it is ready to be manufactured and that it will later become part of its associated system. At this stage, the work of other actors begins that will render the rest of their life cycles eco-effective, with decisions on logistics or management of the end of life. These stages, considered in the design (genomics phase), can be completed and optimized at this point. Hence, in the design stage, certain decisions are made that ease this work and help to minimize the environmental impact once the network of relationships, which ensures the eco-compatibility and metabolism, are established.

Therefore, it is necessary to conduct a study of possible interactions by considering two key elements: Naturesphere (6), which constitutes the environment where the industry extracted the natural resources and where the biological nutrients are returned; and Technosphere (7), as a means of attaining the flow of technical nutrients, which must be taken into account for the material flow analysis (MFA) and substance flow analysis (SFA).

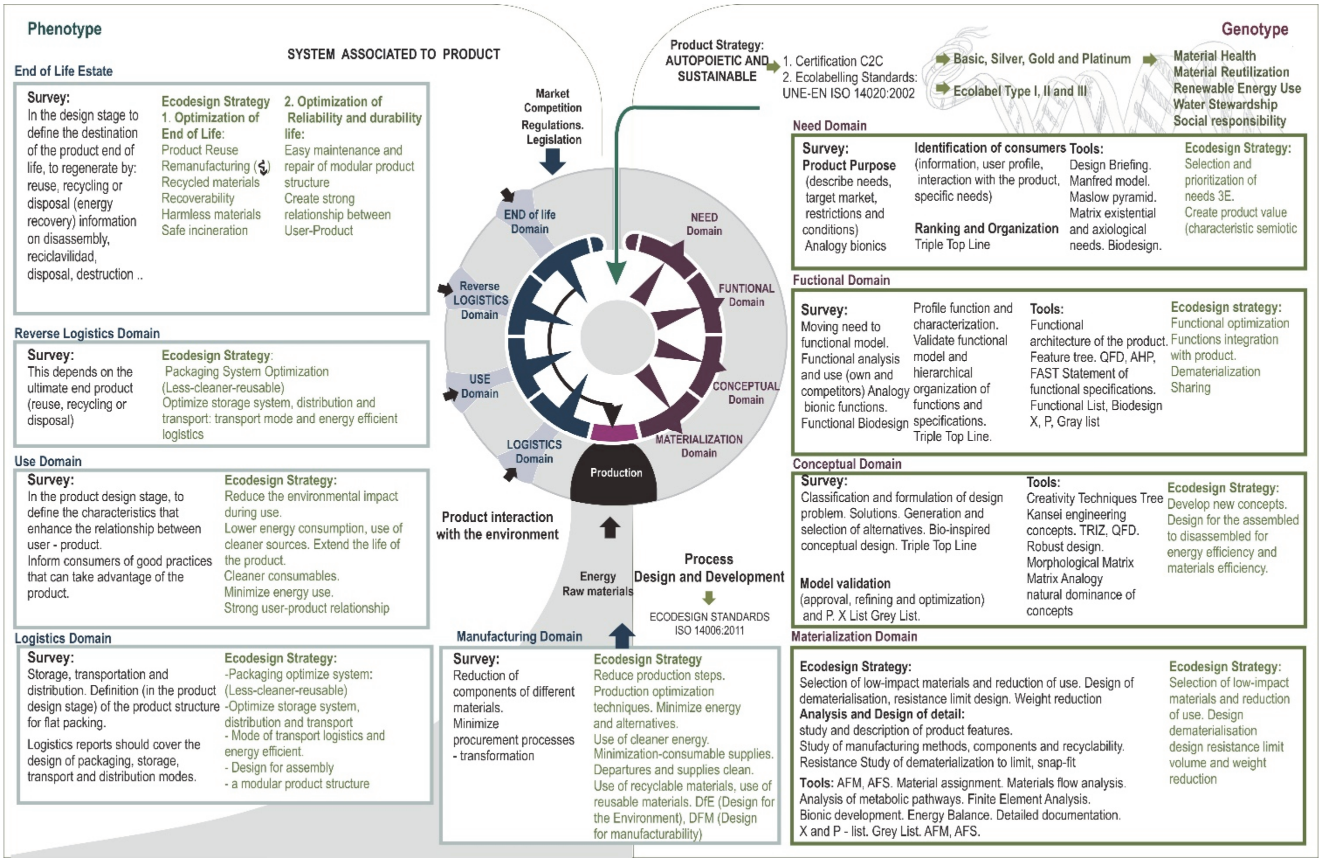


Figure 4 Toolbox MGE2. Definition and Development of MGE2 Strategies and tools; Source: The authors

<Phenotype> (4). This phase constitutes the development of the analysis of the real and potential interactions of the product with the environment as an expression of its genes (genotype + environmental interactions = phenotype). The expected outcome of the product on the market (environment) is determined. This stage takes into account market analysis, legislation, user analysis, material resources available, traditions, forward and reverse logistics, stakeholder analysis, processes of the end of useful life, etc. The required performance of the product is analyzed under the C2C sustainability criteria, based on data obtained from the system into which the product will be integrated and associated.

<Life Cycle Analysis> (5). The objective of LCA is to determine the environmental impact that is associated with the phenotype of a product or with its new design (genotype), so that the impact can be considered within the product.

<Strategy: This tool is particularly significant in the model proposed since it pursues the qualitative and quantitative knowledge of the flows of materials, energy, emissions, and effluents and of their impact on the environment. LCA can be applied at various stages (on the phenotype - product to be redesigned - or on the genomic - design of a new product.

## 4. Verification and Recognition

The MGE2 model is designed to be applied in all those design projects and product development with sustainability goals under C2C. Once the design and development process is completed, then verification and recognition of the work is performed by some of the existing eco-labels, with which the added environmental value is awarded to the products [13]. Thanks to the structure of the proposed model, the criteria demanded by eco-labelling schemes are included in the product once they have undergone the design stages. Together with the current ISO eco-labelling programs [15], a new certification system associated with C2C eco-effectiveness [16] has been developed, administered by the authors of this new perspective and which differentiates products according to the sustainable objectives achieved, into qualifications of *platinum, gold, silver,* and *basic*. The criteria for the achievement of these labels range from the basic level (where the product inventory and strategy is valued), through to the silver level (achieved with a product of at least 50% reusable materials), via the C2C gold level (products consisting of 65% clean materials, production and energy), and finally reaching the Platinum level (which includes all the above requirements and also attains good water management in the life cycle). The structure of MGE2 allows all aspects required for the implementation of the

C2C-certified products to be taken into account, once the necessary tools to enable the estimated requirements to be met are incorporated.

## 5. Case study: implementation of MGE2 in the redesign of office chair

The implementation of MGE2 is flexible, and varies according to the type of project, product complexity, and the proposed objectives. Therefore, the industry can either redesign an existing product or design a new one, adapting to different operating modes in the different stages of the model. That is to say, the MGE2 model offers flexibility of application and flexibility in the choice of techniques and tools destined for the attainment of C2C projects. The exact nature of this methodology is applied by way of an illustration, and defines the strategy and steps to follow in the redesign of an office chair [17,18]

**STAGE 1: Life cycle analysis of existing products:** Life Cycle Analysis is an objective process for the evaluation of the environmental impact associated with a product, process or industrial activity by identifying and quantifying not only the use of material and energy, but also the emissions to the environment, both in order to determine the impact of resource use and emissions, and to evaluate and implement environmental improvement strategies [19]. The study covers the entire life cycle, taking into account all stages from the cradle to the grave of the product involved. For this case study, by following MGE2 and thanks to the study of material and substance flow, this LCA now covers the life cycle from the cradle to the cradle. The main objective of this tool within the model is to determine the environmental impact of product performance in relation to the 3E vectors. From this stage, improvements are established that determine the product strategy. The LCA results obtained are shown in Fig. 8 in the final section.

**STAGE 2: Establishment of product strategy under C2C:** Once the LCA data and possible applicable improvements are known, then a systemic, autopoietic, environmentally compatible and metabolizable strategy of the product is established through the exploration of the value and innovation of the 3E pyramid, which constitutes the basic tool for eco-innovation. The generation of the set of 3E values enables the establishment of the premise that defines the product strategy; this situation in turn enables the parameterization of the environment of the generic design, through techniques and tools for this particular project. This strategy focuses on: (1) Systemic (or holistic) integration for bio-inspired design; the different scenarios of the chair throughout its life cycle are considered in this phase with the aim of promoting and equitably integrating all three aspects of the 3E pyramid. (2) Sustainable and eco-friendly. Improvement of the metabolism by decreasing the ratios of environmental impact on the Naturesphere, in order to minimize the impact on the environment (or rendering the ecological footprint assimilable). This is achieved by increasing the flows of material on the Technosphere by means of upcycling (minimizing those flows related to infra-recycling as much as possible), eliminating possible toxic or polluting substances with the incorporation of innovations from green or sustainable chemicals. Finally, features that are cooperative with Naturesphere are incorporated, thereby creating environmental value. (3) An autopoietic character is obtained by taking the concept of "genetic intelligence" into account and by supplying it to the product with the aim of facilitating tasks of use, manufacturing, logistics (forward and reverse), and of its regeneration at the end of the life cycle. In a particular way, this intelligence incorporates innovation into phenotypic interactions, thereby enabling regeneration, reuse, and recovery in successive generations of products.

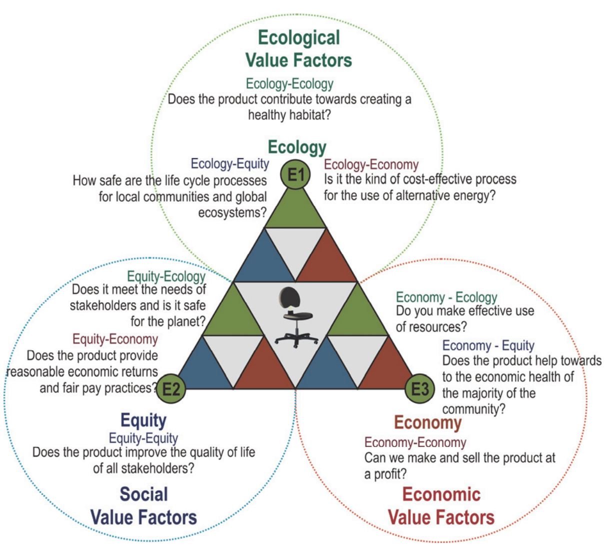

Figure 5 Application of the 3E product pyramid; Source: The authors

**STAGE 3: Design and Development of the product genotype.** Study of the Phenotype and associated criteria: Once the data of LCA, the phenotype required, and the product strategy are all determined, then the redesign is performed under the principles of C2C. To this end, the genomic design is carried out, with the detailed study of each domain, (need, functional, conceptual, and materialization), and in the fields of Eco-innovation, Eco-compatibility, and Metabolization [20]. In each domain, a series of individual eco-design strategies is applied, as are the tools necessary for the definition of all the requirements that render the product sustainable.

**STAGE 4: Validation of genotype and phenotype optimization:** Concurrent with the previous stage, the verification and validation of the genomic design of the product is performed based on the requirement demanded by the system that it be associated with the life cycle of the product, which in turn determines the procedures for interaction of the genome with the environment. This results in the initial phenotype which develops and optimizes over the life cycle and those of successive generations of products. The stages of manufacture and of the end of useful life hold special interest, since the metabolic pathways and biological and technical nutrients are investigated and defined, and fix the associated processes from the disassembly diagram of the genotype. The final solution is the ECOS office chair [17,18].

**STAGE 5: New LCA of the product with the objective of Environmental Product Declaration C2C.** The last stage in the implementation of the MGE2 model corresponds to the completion of a new LCA of the redesign of the product. The objective of this analysis is the confirmation of the proposed improvements in the design process and the knowledge of all the information necessary in order to obtain an eco-label for the product from any of the existing certification programs (including C2C certification). In the case study carried out, the second application of LCA verifies whether the product meets the criteria to qualify for C2C certification [16]. The results awarded a GOLD eco-label to the chair. All the information is collected for the writing of the Environmental Product Declaration in which the environmental information of the chair is presented. It is also quantified throughout its life cycle to allow for its comparison with other products that fulfil the same function, all of which cause a greater impact on the environment.

## 6. Results and Discussion

Fig. 6 presents the results of the MFA, SFA, and LCA, as well as the properties and characteristics of the flows of materials, together with a comparison where the results and impact reduction are described. The final synthesis is summarized in this figure, which reflects the characteristics that render the product sustainable under the C2C paradigm, since they fit the criteria required to achieve the aforementioned certification.The MGE2 model can be used for the design and development of any product and system; data relating to genotype and phenotype, i.e., all that is required are the inputs and outputs of each processes involved in the life cycle stages, properly defined in the system limits of LCA process. The MGE2 model provides an appropriate structure for design and product development from C2C paradigm, unlike other models proposed in the literature which do not contemplate an organization of actuation from the Triple Bottom Line perspective and do not integrate quantitative tools and methodologies that facilitate the application of the C2C principles, such as the Material Flow Analysis (MFA), Substance Flow Analysis (SFA) or life cycle assessment (LCA). Furthermore, the MGE2 model considers the different routes of product certifications. The MGE2 model is currently under validation, conducted by the company *ESINOR Instalaciones* for energy system design and development. Intellectual exploitation rights were given up in order to verify its application in the industrial sector.

The development of the entire life cycle stage is a specific framework to achieve sustainable integration in the design and product development from 3E perspective (economic, ecological and social). For this reason, the scope of this model is open to future updates. We are currently working on the detailed design process of individual product life cycle stages. It is in the manufacturing stage that different methods of design and development of sustainable manufacturing processes are being considered, from new paradigms such as Green manufacturing or Clean Production [29] or the Materialization Domain that is being completed with the study of industrial product metabolism.

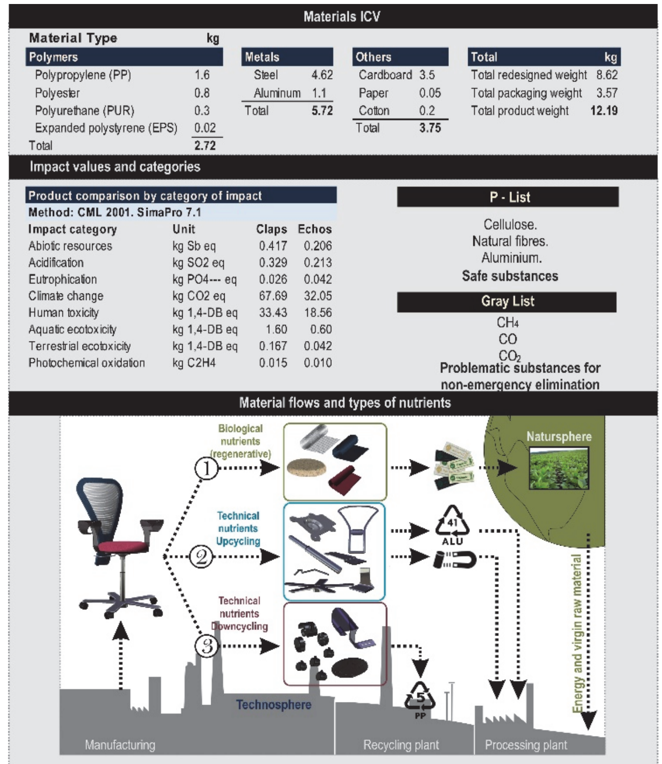

Figure 6 Summary of life cycle analysis and criteria for C2C certification of the product; Source: The authors

## 7. Conclusion

The work presented provides previously unexplored joint epistemological ideas of the C2C perspective and a model of design and development which introduces an articulated form of implementing the basics of this new design paradigm. By compiling lessons learned from the approach of eco-efficiency and eco-innovation, we develop a new bio-inspired architecture for the process of eco-efficient design and development under the C2C principles, known as MGE2. This model can support all regulatory requirements to date, and can extend the range of solutions in order to improve the performance of the minimization of impact and to solve the current environmental problems caused by industry worldwide. Future work is aimed at developing design and development environments with PLM tools and CAD systems that provide computational support of the MGE2 model, by validating and verifying information and offering feedback. This work proposes a methodology to design sustainable products and systems within the C2C paradigm. Its main objective is to optimize any system interactions with the environment, taking into account the Three Sustainable Dimensions: economic, ecological and equity (3E). The Genomic Model of Eco-innovation and Eco-design is a methodology for sustainable product design and development. It can help engineers and their products, systems or activities to have an internal operation in line with its associated system. The model guides decision making processes with both qualitative and quantitative assessments within a set of strategies included in the best available techniques, combining new and eco-innovative methodologies with traditional experienced technologies, obtaining broad effectiveness to manage product lifecycles.

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