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The aesthetics of sustainable industrial design: Form and function in the circular design process

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Abstract

The relationship between form and function has long been a point of debate in the design community. Particularly, the famous principle 'form follows function' has been a focal point of such discussions. Since its introduction, many studies have been undertaken by theorists and practitioners to challenge or disprove this injunction. Furthermore, from the modern perspective of sustainability which has attracted global attention over the past few decades, there is a crucial link between design and sustainability. That is, poor designs, generally, lead to poor products which contribute to environmental and economic degradation. Consequently, understanding the relationship between form and function in design could contribute to a more sustainable environment. In this paper, first, we explore the views of some influential figures of the twentieth century's industrial design on this essentially philosophical, yet practically crucial, axiom of modernism. Then, we propose a design process model for aesthetic-sustainable industrial design drawing on a theory of design aesthetics and the principles of circular design. This model integrates a circular design module into the industrial designer's theory of aesthetics to complement the design process in terms of sustainability. The proposed design process model could help designers establish an appropriate relationship between the form and the intended function of a product to contribute to lowering its environmental impact.

KEYWORDS
aesthetics, circular design process, form–function relationship, functional form, industrial design, sustainability

1 | INTRODUCTION

The relationship between form and function has always attracted considerable attention from the design community. In particular, despite being remarkably widespread in the design literature, the famous axiom 'form follows function' has been criticised by many scholars and practitioners. In recent decades, using a wide range of qualitative and quantitative methods, researchers have tried to shed light on different aspects of formal and functional design in various industries, including automotive (see, e.g. Luccarelli et al. (2014); Sheller (2004)), marine (see, e.g. Gaspar et al. (2012)), building engineering (see, e.g. Ching (2023); Van Der Voordt and Van Wegen (2007)), bridge engineering (see, e.g. Billington and Gottemoeller (2019); Furuta et al. (1995); Kido (1997)) and personal electronic devices (see, e.g. Esfahani and Sareh (2021); Horst (2016); Wang and Li (2017)).

In addition, from the modern perspective of sustainability which has been of particular global significance over the past few decades, there is a crucial link between 'design' and 'sustainability'. That is,

poor designs, generally, lead to poor products which contribute to environmental and economic degradation (Stegall, 2006). As a result, understanding the relationship between form and function in design could contribute to a more sustainable environment.

Simplicity is considered to be a general attribute of environment-friendly products. Fiksel (2009) highlighted the importance of product simplicity, which can be traced back to the Bauhaus movement in the 1930s; he discussed that product design simplicity generally contributes to achieving lower material consumption and manufacturing cost, greater durability, and easier assembly and disassembly. Deutz et al. (2010) investigated the possibility and potential consequences of establishing sustainable waste management as a functional requirement in the design process to achieve environment-friendly products. Based on the general notion of 'responsible design' introduced by Papanek (1985), Leerberg et al. (2010) discussed the necessity of sustainable design as a value to be integrated into design education curriculums to train sustainability-responsible industrial designers. Volstad and Boks (2012) studied the advantages and disadvantages of 'biomimicry', that is the science of imitating or taking inspiration from natural designs and processes to solve human problems (Benyus, 1997), as a tool for industrial designers when sustainability is a goal to achieve. Keitsch (2012) explored the theoretical concepts that underlie sustainable design and presented a set of guidelines for future research and development in this area.

This paper aims to develop a design process model, which could help designers establish an appropriate relationship between the form and function of a product to contribute to lowering its environmental impact. To this end, Section 2 explores the relationship between form and function in industrial design, in which we analyse the perspectives of some prominent thinkers, theorists, and practitioners from the sixteenth century to the current era. Section 3 presents an example of the form–function relationship in industrial design through the study of the bicycle as one of the most ubiquitous products in the modern world. Then, in Section 4, we propose a design process model for aesthetic-sustainable industrial design drawing on a theory of design aesthetics and the principles of circular design. Finally, Section 5 draws some concluding remarks on the findings of this study.

2 | FORM–FUNCTION RELATIONSHIP: AN ANALYTICAL-HISTORICAL STUDY

As an immensely philosophical question, the relationship between *form* and *function* has long been a point of debate in the communities of architecture and design. In Xenophon's Memorabilia (Bonnette, 1994), a collection of Socratic dialogues, Socrates is quoted as saying: '*Is a dung-carrying basket beautiful then?—Of course, and a golden shield is ugly, if the one is well made for its special work and the other badly*'. The art critic Edward Lucie-Smith interprets this as the realisation made by 'intelligent men' of the relationship between the 'idea of beauty' with 'efficiency' and 'appropriateness for use' in everyday objects (Lucie-Smith, 1983). Thinking functionalistically, in 'Of Building - Essay 45' (Bacon, 1632; Lucie-Smith, 1983), Francis Bacon (1561–1626) stated that '*Houses are built to live in, and not to look on; therefore let use be preferred before uniformity, except when both may be had*'. Ideas on such a relationship can also be traced back to the studies of architectural theorist Carlo Lodoli (1690–1761) with the motto '*Devonsi unire fabbrica e ragione / E sia funzion la rappresentazione* (Memmo, 1834)', meaning that '*if making is based in truth, then function will be revealed in the representation*' (Neveu, 2005).

The art historian and philosopher Herbert Read (1893–1968) defined *form* as the '*shape imparted to an artifact by human intention and action*' and highlighted the 'aesthetic connotation' of 'form' that is not carried by the word 'shape'. According to Read's theory (Read, 1965), the development process of the shape of *objects of utility* can be classified into three stages: (1) *discovery*, where the *functional form* is found or invented (here we call such a form the *basic functional form*); (2) *efficiency-driven refinement*, in which the basic functional form is refined to enhance its functional efficiency (and usefulness); and (3) *stylistic refinement*, through which the functional form is refined stylistically to reflect the desired aesthetic or symbolic intentions of the designer. Figure 1 presents different stages of the formal evolution of the functional form for 'the cup' as arguably the most ancient utensil (Hough, 1922), where we can see how primitive liquid-containing geometries, inspired by a partially closed palm of the hand, have gradually evolved to integrate usability- and efficiency-enhancing features such as handles and stable bases.

The theory of functionalism states that *good design* results from or is identical to *functional efficiency* (Curl & Wilson, 2015). The common notion '*form follows function*', abbreviated as $F \Rightarrow f$ in this paper (F and f denote form and function, respectively), is associated with the 'doctrine' of *Functionalism* (Pye, 1978). $F \Rightarrow f$ is attributed to architects Henry Hobson Richardson (1838–1886), Louis Henry Sullivan (1856–1924), and Frank Lloyd Wright (1867–1959), as well as, indirectly, to the sculptor Horatio Greenough (1805–1852; Greenough, 1969; Meikle, 2010; Sullivan, 1956). In his seminal article entitled *The Tall Office Building Artistically Considered*, Sullivan claimed that '*form ever follows function*' was '*the law*' (Sullivan, 1896); the painter and art historian Erle Loran (1905–1999) considered $F \Rightarrow f$ as a *creative ideal* (Greenough, 1969); and the contemporary design historian Jeffrey Meikle named it as an *injunction* (Meikle, 2010). Many others consider $F \Rightarrow f$ to be a fundamental *axiom of modernism* (Butler et al., 2003; Ostwald & Dawes, 2018; Palmer, 2003), a *dictum* (Hendrix, 2013; Michl, 2009), a *credo* (Bürdek, 2005) or the *interwar mantra* (Betts, 2004).

It should be noted that this expression (i.e. 'form follows function') is a conceptually moderated version of the original statements by Sullivan and Wright, who, respectively, stated 'form *ever* follows function' (Sullivan, 1896) and 'form does not follow function; form and function are *one*' (Kiss, 2017; Kruft et al., 1994; Lipman & Wright, 2003; Wright, 2005).

Several other theorists and philosophers also discussed such interrelations; for example, in *Conduct of Life*, the philosopher Ralph Waldo Emerson (1803–1882) states: '*Beauty rests on necessities. The line of beauty is the line of perfect economy*'. He adds: '*We ascribe beauty to that which is simple; which has no superfluous parts; which*

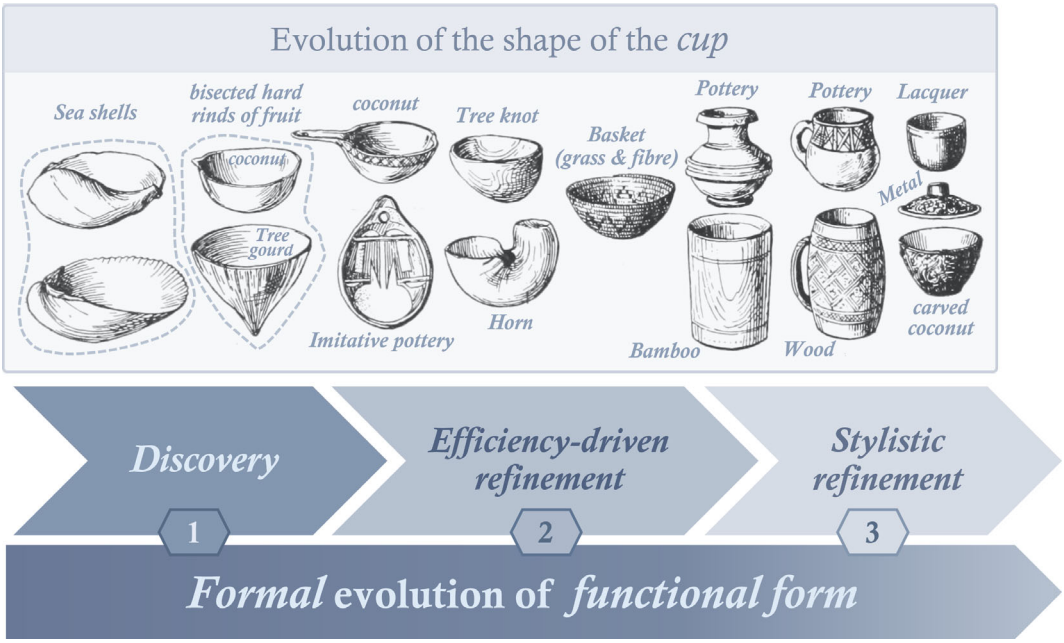

FIGURE 1 A diagram representing the formal evolution of the *functional form*; as an example, typical cups at different stages of evolution are illustrated (the drawings of the objects are adapted from [Hough, 1922]).

exactly answers its end'. To further elaborate on these statements, Emerson gave natural examples including the geometry of bee cells, which leads to maximal strength for a given amount of wax, as well as the bones or the quill of birds that provide maximal strength for a given weight (Emerson, 2012; Emerson, 2018a; Emerson, 2018b). Emerson's statements manifest how *form*, and particularly what he considered to be '*beautiful form*', is meant to serve what he called the '*necessities*' or the '*end*', which constitute what we call the *functional requirements* of the design.

Despite its widespread appearance in the literature, $F \Rightarrow f$ is criticised by many designers and scholars. In an article published in *Art & Industry* in 1938, Barnes and Reinecke stated: '*Such criteria as 'form follows function' are unsound because their first premise is unsound. They make the error of assuming that there is one, and only one right way of doing a thing. This is a hangover from the Platonic postulate of an eternal and immutable ideal form inhabiting a misty other world*' (Barnes & Reinecke, 1938). The industrial designer Dieter Rams (born 1932) stated that despite its striking clarity and simplicity, $F \Rightarrow f$ '*never was and never will be a universal rule*' (Rams, 1983). Instead, in his famous 10 'basic hypotheses' (Klemp & Ueki-Polet, 2015), 'design principles' (Klemp, 2012) or 'principles of good design' (De Jong et al., 2017), Rams postulates that '*good design is aesthetic, because the aesthetics of a product, and its fascination, are intrinsic parts of its function and utility*' (Rams, 1992). The other German industrial designer Jochen Gros (born 1944) considers $F \Rightarrow f$ to be 'inapplicable' to the design of electronic equipment, because '*microelectronic building blocks have themselves design potential and require their own organisational criteria*' (Gros, 1989). The design theorist Bernhard E. Bürdek (born 1947) describes $F \Rightarrow f$, which was the dominant rule of product design in Germany until the 1980s, as an approach aiming to develop '*design solutions possessing maximum functionality based on an analysis of the needs of society*'. He outlines the limited scope of the concept of *function*, which incorporated only practical or technical aspects such as handling and ergonomics, overlooking the '*communicative dimension*' of the product (Bürdek, 2005). The rationale of such an argument is also reflected in expressions such as 'form beyond function' (Inglis, 1988; Walker, 2011a) and 'form follows meaning' (Hattenhauer, 1984; Krippendorff, 1993), which tend to take design '*beyond the instrumental logic of production efficiencies*' (Walker, 2011b).

In response to such criticisms, one might argue that 'form' has a *metaphysical* 'function' to represent an idea or express a feeling (Hendrix, 2013). Similarly, Cairo (2012) discussed that 'function' in $F \Rightarrow f$ is not a task-oriented goal to be achieved by the designed entity as a 'tool', but is an 'intrinsic' or 'essential' property of both natural and artificial entities. However, in the context of architecture, theorists have widely used these two terms in their certain modern connotations, avoiding such metaphysical interpretations (Arnheim, 2009; Eisenman, 2018; Frankl et al., 1968). According to Hendrix (2013), 'form' refers to the visual shape or appearance of the structure including line, outline, shape, and composition, whereas 'function' relates to the structural and functional requirements of the structure such as construction, shelter, organisation, use, occupancy, materials, and social purpose. In particular, in the context of built environment structures, Fritz Leonhardt (Leonhardt, 1996) highlighted the misleadingness of $F \Rightarrow f$ if the function is 'only defined structurally'. Papanek (1985) expressed the true 'implication' of $F \Rightarrow f$ as being 'as long as the functional requirements are satisfied form will *follow* and *seem pleasing*' and emphasised that it does not imply that '*ideal* form will always work well'.

There are also several cases of disputable use of $F \Rightarrow f$ in some highly credible sources. For example, when discussing the exterior

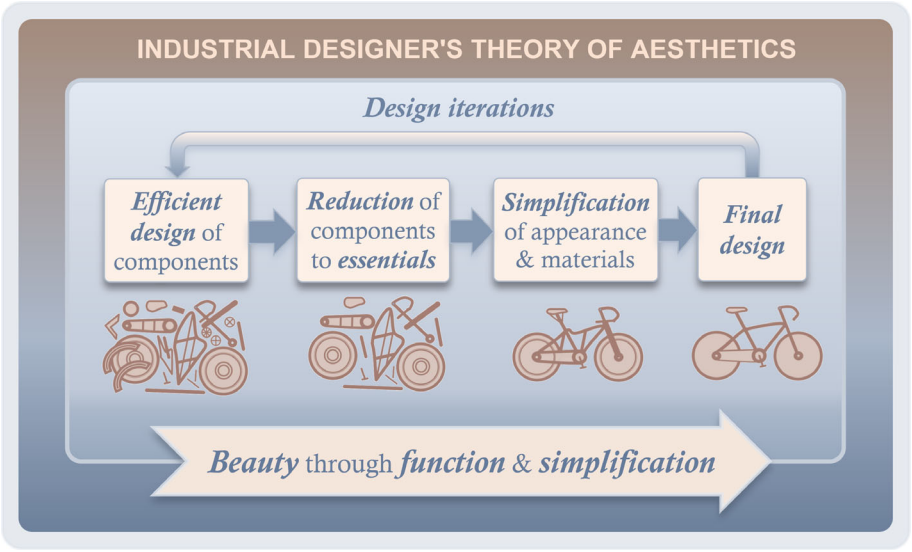

FIGURE 2 A design process established based on Loewy's *industrial designer's theory of aesthetics* accompanied by a schematic representation of the design process of a typical modern road bike.

design of a 1915 Pierce-Arrow, Meikle (2010) claims: 'The body did not express the obvious function of the Great Arrow as a transportation machine. But it did, nevertheless, express an image of the auto's function-an image presumed attractive to potential upper-class customers. In the thirties, designers sought to represent an image of speed in their automobiles. In 1915, however, the image of the Pierce-Arrow was "class"'. He adds: 'In a general sense the 'function' of the Pierce-Arrow was 'to get itself sold', and in that sense form did follow function'.

One can argue that the claimed function 'to get itself sold' is not a 'function', but is merely the commercial goal of all designed products on the market regardless of their form and function. On the relationship between a product and its commercial success, the industrial design pioneer Henry Dreyfuss (1904–1972) stated: 'Truly, the manufacturers could sell anything', mentioning the case of 1948 Cadillac the rear fishtails of which initially seemed 'out of place', but they gradually became popular as a 'symbol of quality' and were broadly adopted by other car manufacturers. Furthermore, he believed that automotive design trendy elements, which had nothing to do with the efficiency or beauty of the vehicle, negatively influenced the 'trends in taste' of other consumer products (e.g. toasters and typewriters), leading to what Dreyfuss considered 'bad design'. However, promoted by the dominant automotive industry, these 'shameless imitations' were promoted into public acceptance. He also pointed out that a bad design which is commercially successful is still a bad design (Dreyfuss, 2003).

The prominent industrial designer Raymond Loewy (1893–1986) argued the validity and applicability of functionalist theories, in particular, statements such as 'anything functionally correct is bound to be correct in appearance' or 'if it works well it looks good'. He considered such general rules to be applicable to 'simple objects' the design of which had reached perfection, making them functionally correct and aesthetically harmonious (e.g. the needle, the ploughshare, and the ship propeller). Loewy discussed that, on the contrary, such functionalist theories are not valid for complex machinery (e.g. a threshing machine, a cotton picker, or a textile loom), which are functionally satisfactory whereas 'their appearance is messy and disorganised', and 'their ensemble is disturbing'. He concluded that 'function alone does not necessarily generate beauty', but 'simplicity is the deciding factor in the aesthetic equation'. Loewy proposed an 'industrial designer's theory of aesthetics', describing the process as creating '*beauty through function and simplification*', and considered the responsibility of the designer to 'establish simplicity through order' (Loewy & Porter, 2002). The flowchart given in Figure 2 represents a design process established based on Loewy's industrial designer's theory of aesthetics. We can see the manifestation of the same idea in one of the 10 principles of good design proposed by Dieter Rams, that is '*good design is as little design as possible*' because 'it concentrates on the essential aspects', formulated as the instructional rule '*omit the unimportant*' for designers (Rams, 1984; Rams, 1992). Importantly, this principle is one of the main engineering design guidelines in the general practice of *design for manufacturing, assembly, and environment* (*DfMAE*), which is nowadays widely adopted in the industry (for more details, see, e.g. Pugh and Clausing (1996) and Boothroyd et al. (2010)).

Another highly influential American industrial designer, Norman Bel Geddes (1893–1958), expressed a similar viewpoint in his seminal book *Horizons* (Geddes, 1977): '*When the motor car, bus, truck, and tractor have evolved into the essential forms determined by what these machines have to do, they will not need surface ornamentation to make them beautiful. Their beauty will be inherent and that will be all the beauty that they need. This is not meant to indicate that if the engineer does his job well the result will be beautiful. Here is where the artist is essential, for he knows how to make a thing of beauty with the minimum of means*'. This statement implies that a functional design is not necessarily beautiful, but a sufficiently evolved machine would have reached a development state incorporating merely '*essential forms*' in which it would be *inherently* beautiful without any nonfunctional aesthetic features. It also implies that such a level of beauty would be achieved '*with the minimum of means*', which can be considered to be equivalent to the principle of 'reduction to essentials' in Loewy's industrial designer's theory of aesthetics.

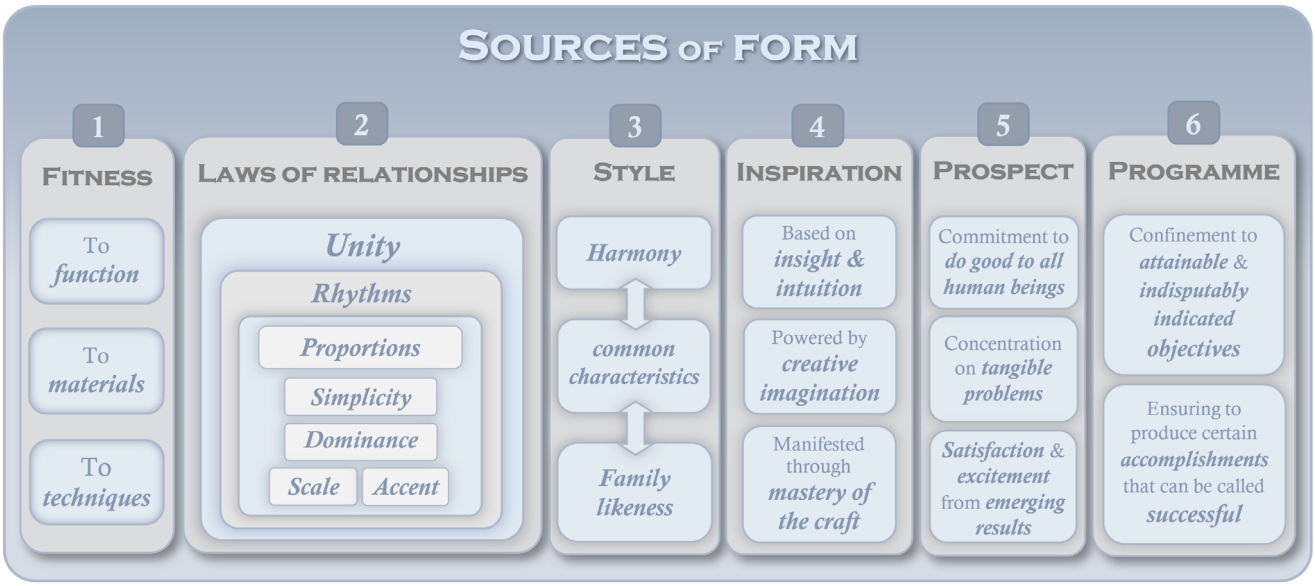

FIGURE 3 A diagram for Teague's framework of '*sources of form*'.

The industrial design pioneer Walter Dorwin Teague (1883–1960) defines design as '*the art of enforcing order on material substances for our service and satisfaction—to be made in terms of our own special circumstances*' (Teague, 1940). Discussing in the context of preindustrial society, he considered that there was a *right form* for any object that evolved through a typically laborious process of trial and error by handicrafts. This definition can be correlated with the expression by German designer Frederick Henri Kay Henrion (1914–1990) who described design as '*an ordering process, creating at its best an inspired, new and unique order from a state of chaos* (Lucie-Smith, 1983)'. In Teague's perspective, '*inward soundness and rightness*' is the result of a '*perfectly functioning order*'; and *beauty* is a '*visible evidence*', *or* '*outward revelation*', manifesting such an inward attribute (Teague, 1940).

Describing the right form as the '*ultimate form that will most perfectly satisfy its maker and serve its user*', Teague tried to develop a general theory for the form-finding of man-made objects and products in the industrial society of the twentieth century. According to his theory, there are six sources of form represented and classified in Figure 3. The first source of form in Teague's framework is '*fitness*' which is divided into three phases: fitness to *function*, fitness to *materials*, and fitness to *techniques*. The principle of fitness states that the final form of any object must be evolved naturally to fit its intended function, constituting materials and manufacturing techniques. The second source of form in this framework is called the '*laws of relationships*', which comprise certain arrangements of elements, including lines, areas, shapes, colours, and masses. Such relationships are the outcome of interactions of these elements rather than being the intrinsic attribute of these individual elements. The laws of relationships realise the basic principle of '*unity*', the achievement of which leads to conceiving the object as a whole. To this end, the elements of design need to have a '*rhythmic structure*', where 'proportions' are the principal means of creating rhythms. Teague believed that '*the laws of relationships have the same kind of universal application as the laws of mathematics, to which they are closely related. It is even probable that they are identical, although no one has explored them with sufficient thoroughness to complete the identification*'[1] (Teague, 1940).

Teague regarded '*simplicity*', which requires us to 'strip off non-essentials', as a necessary criterion for achieving unity in modern design, a crucial point that he believed was not considered to be necessary in previous eras. He particularly stated: 'Other ages have not felt the force of this necessity as strongly as we feel it: but for us, in design as in science, no solution of a problem can be right so long as a simpler, more direct, and equally practical solution can be found'. This statement again highlights Teague's functionalist approach to form-finding in design. In other words, he considered the laws of relationships to be tools for solving what he called 'problems of fitness'.

According to the historian Roland Marchand (1933–1997), Teague's vision of '*radical simplicity*', that is his strong tendency to '*enhance design aesthetics and effectiveness through simplification*', was not only observable in his designed products but could be also seen in his theatrical designs for industrial exhibitions (Doordan, 1995; Marchand, 1991).

Teague also took into account three other factors which are necessary for the perfection of the rhythmic structure: (1) the 'dominance' of a single theme or motif; (2) to be constructed within a comprehensible 'scale'; and (3) to be marked by 'accents' that visually guide us to perceive relationships (Teague, 1940).

[1]Birkhoff's Aesthetic Measure was first published in 1933. While Teague raised this question in *Design This Day—The Technique of Order in the Machine Age* published in 1940, there was no mention of Birkhoff's efforts to formulate such relationships mathematically in his book. (Teague was either not aware of Birkhoff's work or had not found it of '*sufficient thoroughness to complete the identification*'.)

Teague had a practical, and to some extent functionalist, approach to 'style', as the third source of form. He opposed any *active attempt to apply* a style to a design, and even to '*identify it with specific forms*', because he considered it to be continuously evolving until it '*ceased to live and change*'. He believed that an '*authentic style*' is a natural outcome of an appropriate response to a certain design problem arising from a real need at a specific time, which through evolution, would result in the integration of the designer's work into a '*satisfactorily unified pattern*'; this would unavoidably lead to spreading a '*degree of harmony*' and '*family likeness*' in their designs, mainly because of the frequent appearance of certain *common characteristics* which would distinguish those specific design works from the works of any time in the past. Nevertheless, Teague does not deny the partial influence of the designer's personality in the formation of their style. Meikle (Meikle, 2005) describes Teague's own style to be 'tended towards an austere neoclassicism appropriate to his rationalist philosophy'.

Inspiration is a source of form in Teague's framework, which cannot be acquired or exercised, but needs the illuminating support of '*insight and intuition*', powered by '*creative imagination*' as well as the designer's '*mastery in their craft*', which would provide the designer with an appropriate *prospect*, as the next source of form. Commitment to do good to all human beings is at the centre of Teague's prescription for prospect, followed by concentration on *tangible problems*, and deriving satisfaction and excitement from gradually emerging visible results.

Such a prospect will lead to the construction of a *programme* formed around *attainable* and *indisputably indicated* objectives. The programme should produce certain accomplishments that can be considered as successful. Teague also spotted a major distinction between humans and other creatures on earth that make things (e.g. spiders that make webs) which he called the '*monopoly of dissatisfaction*' (Teague, 1959); that is, we accept man-made objects are never perfect, so we are on an endless quest to make better things.

It can be observed that Teague's framework includes a wide range of factors which contribute to *form-finding* in design, a process he called '*evoking rightness of form*'. It is not necessarily comprehensive to be used nowadays, because aspects such as ergonomics, user interactions, environmental friendliness, and sustainability were not driving factors in the first half of the twentieth century. Nevertheless, Teague's framework proposed a useful approach to the design of a wide range of products, which could be beneficial to industrial designers even today.

The prominent automotive designer Frank Stephenson proposed a more neutral version of 'form follows function' as 'form *equals* function', stating that 'if it looks right, it *is* right'. The given example for this notion is the McLaren MP4-12C the exterior design of which was dictated by engineering virtues such as lightweight, low height, appropriate mass distribution, good visibility, and desirable down-force without excessive drag. It is believed that McLaren designers 'imaginatively' created a body shape, which desirably addressed the engineering requirements of aerodynamics, handling, and heat transfer (Codling, 2011).

Another revision on $F \Rightarrow f$, made by Jim Lesko (Lesko, 2007), is expressed as 'form is the *resolution* of function'. This statement attributes a more 'active' role to 'form', compared with its passive role in $F \Rightarrow f$ where the function is the main influencing component of design. This revised version of $F \Rightarrow f$ allows us to consider other design and development aspects such as manufacturability and materials as parts of the design process.

In particular, Loewy criticised the overwhelmingly stylistic approach to the design of American cars of the 1950s, which was in overt conflict with his ideals, and had led to a typical car which was oversized, too expensive, and too high maintenance, with him describing it as a 'jukebox on wheels' (Atlantic-Monthly, 1955; Fortune, 1947; Gartman, 2013). Importantly, such a vehicle was also an offence against the 'principle of austerity' affiliated with the 'modern movement' (Mathias et al., 1998). It can be seen that in this case, Loewy's industrial designer's theory of aesthetics was in line with the socioeconomic values of modern society.

3 | FORM–FUNCTION RELATIONSHIP: A DESIGN EXAMPLE

In this section, we present an example of the form–function relationship in industrial design through the study of one of the most ubiquitous products in the modern world: the bicycle.

Bicycle designers had long realised that from a safety perspective, it was best to position the rider's seat within the distance between two wheels of moderate size (Wilson et al., 2020). Following years of developing this idea, in the late 19th century, the concept of 'safety' bicycle emerged as an alternative to the penny-farthing bicycle, which was also known as the *high-wheel*, *high-wheeler*, or *ordinary* bicycle. 'Rover Safety' was the first commercial safety bicycle with direct steering and a geometric frame configuration close to the *diamond frame* used in most modern bicycles. The inventor, John Kemp Starley (1855–1901), explained the main principles guiding him to this novel design to be based on four requirements as follows: (1) to place the rider at an appropriate elevation from the ground; (2) to connect the cranks with the driving wheel to facilitate easy gear change; (3) to place the seat in an appropriate position in relation to the pedals; and (4) to place the handles in a suitable position in relation to the seat to maximise the rider's force on the pedals and minimise the rider's amount of effort and consequent fatigue (Penn, 2012; Pickup, 2015; Starley, 1898; Tovey, 2016).

The structural design of the modern diamond-frame safety bicycle, as depicted in Figure 4a, is considered a remarkable example of *functional form* that has been the dominant design configuration for more than a century. Bicycle mechanic and author Sheldon Brown considered the diamond frame 'the standard design for a bicycle frame' and 'one of the most nearly perfect pieces of design known, due to the extreme amount of refinement it has undergone over the last century, and its purity of form' (Brown, 2008; Penn, 2012). As can be seen from Starley's design principles, this dominant form was developed merely based on structural, mechanical, and ergonomic

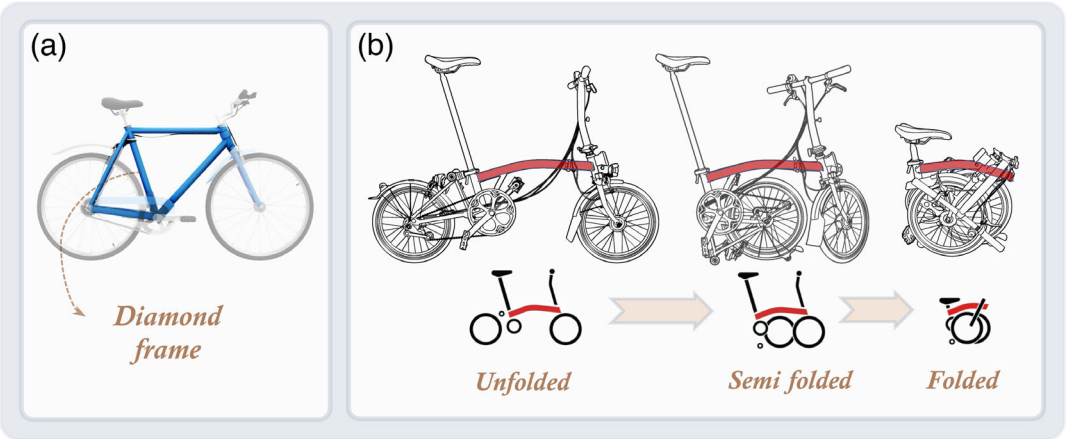

FIGURE 4 (a) The diamond frame of a typical modern bicycle. (b) Schematic representations for the reconfiguration sequence of the Brompton folding bicycle.

requirements, without any particular intention, at least consciously, to create a design of certain aesthetic properties such as any specific appearance or style. In this regard, Hadland and Lessing (2014) proposed the 'contention' that 'most of a bicycle's aesthetic characteristics derive primarily from engineering, which is one of the reasons why bicycles are such pleasing creations'.

It is a notable fact that as new functionalities are added to a product as it evolves, an updated form must be adapted to fulfil or facilitate the new functionalities or functional requirements. Again, the bicycle provides us with a simple but remarkable example: the folding bicycle. In particular, considering the iconic Brompton folding bicycle, the curved form of the cross-bar (i.e. the main tube shown in red in Figure 4b) is a mere consequence of 'foldability' as a major 'functional requirement' (Hadland & Lessing, 2014).

4 | A FRAMEWORK FOR AESTHETIC-SUSTAINABLE INDUSTRIAL DESIGN

In general, a product that is developed to be reused must be designed and manufactured differently from other products (Desai & Mital, 2020). *Circular design* is a design approach based on the circular economy model that facilitates the creation of products that can be reused, repaired, or recycled when they reach the end of their life cycle. Norman defines circular design as a process in which the selected materials have minimal impact on the environment and the product can be disposed of in such a manner that '*enhances the ecosystem through decomposition or as a source of useful energy*' (Norman, 2023).

The circular economy has three design-driven principles as follows: (1) eliminate (or maximally minimise) waste and pollution; (2) maximise product lifespan through circulating products and materials (at their highest value); and (3) regenerate natural systems (Cie, 2023; Macarthur, 2013).

In this section, we propose a framework for aesthetic-sustainable industrial design drawing on the industrial designer's theory of aesthetics (introduced in Section 2) and the principles of circular design, represented by a flowchart in Figure 5. As can be seen from the figure, the aesthetic-sustainable industrial design framework involves achieving 'beauty through function and simplification' concurrent with attaining sustainability through the three principles of circular design.

Here, we propose a design process model based on the above-mentioned framework for aesthetic-sustainable industrial design. This model, as depicted in Figure 6, integrates a *circular design module* into the flowchart of the industrial designer's theory of aesthetics to complement the design process in terms of sustainability. This module, shown in green and expanded in the lower part of Figure 6, incorporates three domains for making design decisions to contribute to sustainable industrial design, as follows:

1. ***Life cycle and reuse strategy***: Designers should maximise the lifespan of products, facilitate product reuse and facilitate easy disassembly and recycling.
2. ***Materials selection***: Designers should minimise unsustainable materials and maximise recycled materials in their design.
3. ***Manufacturing processes***: Designers should minimise pollutant and wasteful manufacturing processes.

An important note is that, given Teague's prescription for prospect, environmental sustainability can be classified under 'commitment to do good to all human beings' and 'concentration on tangible problems' in the current century.

In 2022, the British manufacturer Brompton Bicycle claimed that 96% of their global operational energy, from brazing torches in their factories to workshop lights in their stores, is sourced through renewable energy and carbon-neutral gas contracts. They have also reported their target to increase this percentage to 100% by 2025. In addition to energy sources, the manufacturer reported that efficiency improvements across their London and Sheffield factories in 2022 contributed to a 9% reduction in emissions per bike in comparison with 2021. Furthermore, according to the Zero Waste to Landfill Policy, all of their

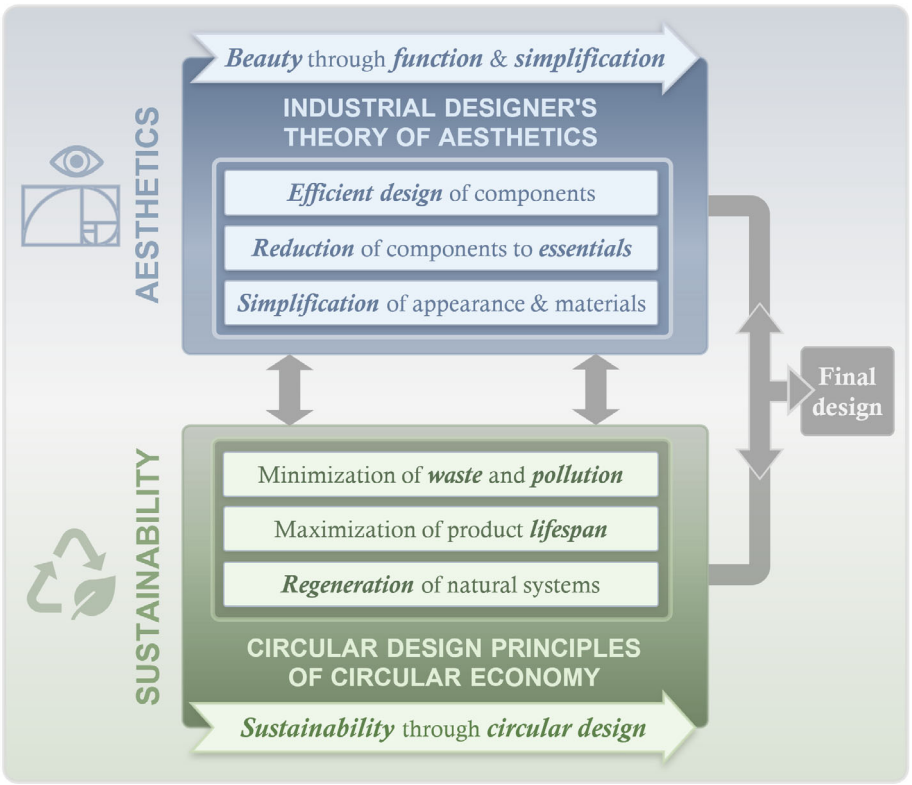

FIGURE 5 A framework for aesthetic-sustainable industrial design drawing on the industrial designer's theory of aesthetics and the principles of circular design.

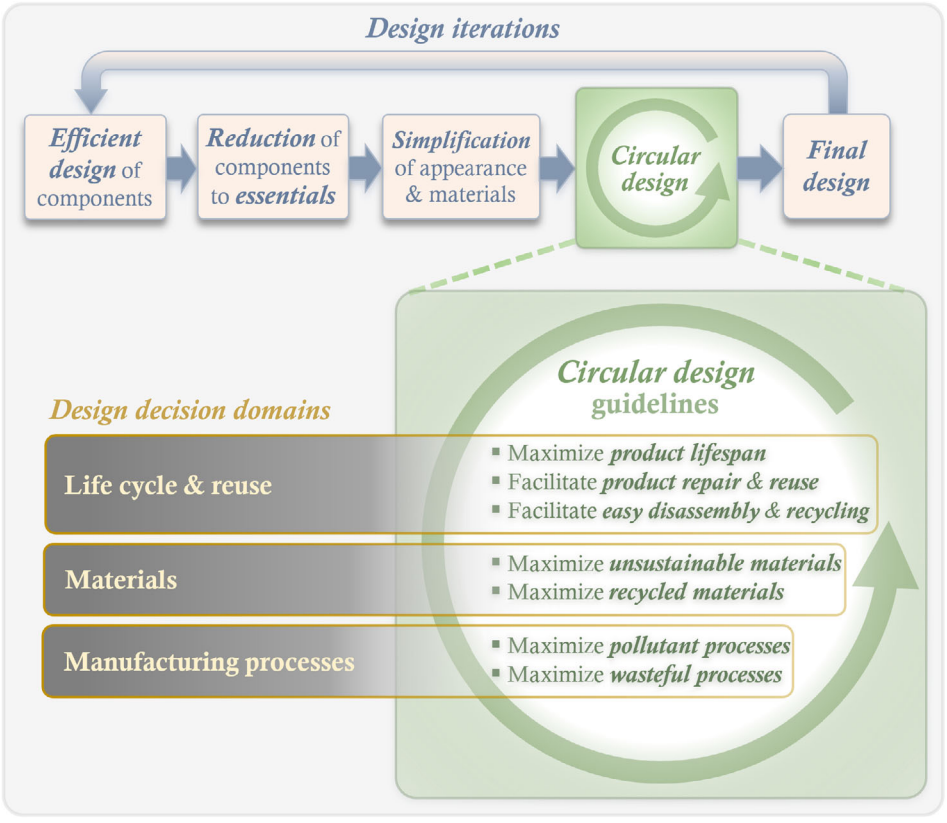

FIGURE 6 A design process based on the framework for aesthetic-sustainable industrial design drawing on the industrial designer's theory of aesthetics and the principles of circular design.

waste was repurposed or recycled into something else. They reached a 70% recycling rate in their London Factory in 2022 and are working towards a 90% rate by 2025.

It is important to note that the principles of circular design are not applied only to the materials and manufacturing processes of the 'final' product, but they should also be applied to all the integral parts

FIGURE 7 The cycling industry sustainable packaging vision to reduce plastic packaging and eliminate unnecessary packaging from the supply chain launched by Cycling Industries Europe (CIE) and the Confederation of the European Bicycle Industry (CONEBI; produced based on [Cie, 2023]).

of the product development and delivery processes, including 'packaging'. To this end, the Confederation of the European Bicycle Industry (CONEBI) and Cycling Industries Europe (CIE) have created a shared vision for the cycling industry that covers all packaging materials (Cie, 2023). This vision, which is based on guidelines containing nine principles, is presented as an infographic in Figure 7.

In particular, for plastics, this vision is closely aligned with the vision of the Ellen MacArthur Foundation's 'New Plastics Economy Initiative' (Cie, 2023). In the pursuit of this vision, Brompton Bicycle reported that 88% of their packaging material was 100%-recyclable cardboard in 2022. Furthermore, the polybags they use are made from 30% post-consumer waste (Brompton, 2023).

As can be seen from Figure 7, the first two principles of this vision, that is efficient packaging design to minimise empty space and redesign to eliminate unnecessary and problematic packaging, are closely aligned with the three principles of Loewy's industrial designer's theory of aesthetics, that is 'efficient design of components', 'reduction of components to essentials' and 'simplification of appearance and materials'. Furthermore, the eighth principle which states 'all packaging is free of hazardous chemicals, and the health, safety, and rights of all people involved are respected' can be considered in the context of Teague's framework of sources of form to be relevant to 'prospect', and in particular 'commitment to do good to all human beings'.

5 | CONCLUSIONS

In this study, we explored and analysed the perspectives of some prominent thinkers, theorists, and practitioners from the sixteenth century to the current era on the relationship between form and function. The study included the analysis of viewpoints by philosophers such as Francis Bacon, Ralph Waldo Emerson, and Herbert Read, as well as some influential figures of the twentieth century's industrial design, including eminent designers Walter Dorwin Teague, Raymond Loewy, Norman Bel Geddes, Henry Dreyfuss, and Dieter Rams, and design historian Jeffrey Meikle.

We presented an example of the form–function relationship in industrial design through the study of the bicycle as one of the most widespread products in the modern world. It was shown that this dominant form was developed merely based on structural, mechanical, and ergonomic requirements, without any particular intention, at least consciously, to create a design of certain aesthetic properties such as any specific appearance or style.

Drawing on the industrial designer's theory of aesthetics and the principles of circular design, we proposed a framework for aesthetic-sustainable industrial design, followed by a design process model based on the framework. This model integrated a circular design module into the industrial designer's theory of aesthetics to complement the design process in terms of sustainability. By establishing an

appropriate relationship between the form and the intended function of a product, designers can contribute to minimising raw material consumption and manufacturing cost, as well as producing simpler systems with easier assembly and disassembly, which could lead to a more sustainable environment.

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