Heliyon

Received:
22 October 2016
Revised:
1 March 2017
Accepted:
24 April 2017

Heliyon 3 (2017) e00299

Revisiting classical design in engineering from a perspective of frugality

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Abstract

The conservative nature of design in engineering has typically unleashed products fabricated with generous amounts of raw materials. This is epitomized by the *factor of safety* whose values higher than unity suggests various uncertainties of design that are tackled through material padding. This effort proposes a new *factor of safety* called the *factor of frugality* that could be used in ecodesign and which addresses both rigors of the *classical* design process and quantification of savings in materials going into a product. An example of frugal shaft design together with some other cases has been presented to explain the working of the *factor of frugality*. Adoption of the *frugality factor* would entail a change in design philosophy whereby designers would constantly make avail of a rigorous design process coupled with material-saving schemes for realizing products that are benign to the environment. Such a change in the foundations of design would abet the stewardship of earth in avoiding planetary boundaries since engineering influences a significant proportion of human endeavors.

Keywords: Safety engineering, Mechanical engineering

1. Introduction

Nature, as a *minimalist*, has created most of the *flora* and *fauna* on earth with an eye on economizing the consumption of available raw materials (Ball, 2009). In contrast, since the dawn of the industrial revolution, designers have been typically

http://dx.doi.org/10.1016/j.heliyon.2017.e00299

using materials in excess of their requirements for achieving safety in the functioning of their products. This excess-material or padding is provided to address the various uncertainties envisaged during the design process including scenarios of overloading; accuracy of theoretical models; materials and manufacturing; to name a few (Carper, 2001; Ullman, 2003; Wang et al., 2014, 2016). Consequently, conservative designs inevitably consume more raw materials (Moynihan and Allwood, 2014; Mufti et al., 2005) and other resources to achieve their functionality with this excess translating into several products that could be fabricated with an eye on economy. In addition to irreversible draining of limited stocks of resources (Bardi, 2014; Gordon et al., 2006), the extra raw materials going into a conservative design would also translate into higher energy consumption and the concomitant emission of *green house gases* (GHG) (Moynihan and Allwood, 2014) from activities needed to procure raw materials in a specified form (IPCC, 2006). Other than planetary impact, conservative designs could also translate into higher costs (Duncan, 2000; Mufti et al., 2005). An instance of this all-around wastage is seen in the large tonnage of steel used in the construction industry due to selection of standardized components (Wise et al., 2013a). Another example is civil structures that continue to be conservatively designed and later fabricated to suppress failures (Moynihan and Allwood, 2014; Mufti et al., 2005). Therefore, the urge to being conservative in modern design runs counter to the need of our time (Bardi, 2014; Gordon et al., 2006). In particular, planetary crises (Steffen et al., 2011) compounded by an increasing population warrant economic utilization of earth's resources. Therefore, a revision in the design process is in order to account for the realities of this epoch. The prominence of engineering in the global economy (NAE, 2002) makes such a change in design imperative for achieving better standards of living while seeking solutions for tackling planetary crises.

Hitherto, there have been several instances of streamlining design for good performance, e.g., designs based on minimum material or light weight constraint (Moynihan and Allwood, 2014) and lower *factors of safety* (Beeby and Jackson, 2016; Duncan, 2000); the Stradivari violin and; the Velodrome for the 2012 Olympic Games in London, UK. (Wise et al., 2013a). In recent years, the advent in emerging economies of low-cost *frugal-innovations* with a no-frills structure, whose realization is constrained partly by scarcer material resources (The Economist, 2010), has been also roped into the private sector epitomized by companies like General Electric of the United States. In fact, material conservation has played a partial role in motivating the proposition of a *National Network for Manufacturing Innovation* (NNMI) in the US to counter the threat, among others, of low-cost manufacturers from emerging economies (NSTC, 2013; Nature, 2014).

The urge to design products for all round *sustainable development* has led to the advent of methodologies such as design for circularity (Ghisellini et al., 2016),

http://dx.doi.org/10.1016/j.heliyon.2017.e00299

design for dematerialization (Van Ewijk and Stegemann, 2014) and product/service-system design (Vezzoli et al., 2015). These approaches, which are rooted in sustainability, conserve materials by reusing, recycling and reduction mechanisms; controlling material throughput through each stage of product *life cycle*; and offering a mix of products and services that cater sustainably to the needs of society; respectively. A widely popular approach is ecodesign that focuses on reducing environmental impact throughout the product-life-cycle comprising manufacturing, use and end-of-life (Roozenburg and Eekels, 1995; Rossi et al., 2016). The holistic nature of ecodesign subsumes the above design-methodologies with material-conservation being one of its features. However, ecodesign has had restraints in its real-time employment (Brones and de Carvalho, 2015) not least due to the lack of metrics that can readily quantify its efficacy. Hence a metric combining *classical* design with frugality could be used in supporting and also quantifying either the methodologies of ecodesign or *classical* design with emphasis on material-savings. It should be noted that the term *classical* refers to design traditionally based on the utilization of principles in *strength-of-materials*, *mechanics* and *materials science* for achieving a suitable *factor-of-safety*. This categorization has been adopted to distinguish and also facilitate development of the proposed *frugality factor* that is built on the *classical* model.

Therefore, there is a need for a suitable metric that besides donning the role of traditional *factor of safety* also quantifies material-savings in various aspects of product-cycle, including design, manufacturing and end-of-life and, whose widespread usage in design would encourage engineers and product developers to conserve resources. Although *Life Cycle Analysis* (LCA) is a vital tool (Bonou et al., 2016) for assessing environmental impacts of products (Consoli et al., 1993), it does not lend itself to a simple representation with the output being a strict function of accurate input data (Telenko et al., 2016). This paper expounds on the development of the *factor of frugality* – an extension of the *classical factor-of-safety* – for quantifying the thrifty use of raw materials going into a product designed for quality performance and also safety.

2. Background

Although *classical* principles are responsible for the bulk of "padded-designs", they can be used in the context of minimizing resource consumption. Such a change can be effected through schemes rooted in design theories both old or *classical* and new. The designer could directly apply such schemes individually or in combination to the problem at hand. Consequently, some schemes aiding frugality in consumption of raw materials are described in the subsections to follow. The content of these subsections underscore the possibility of conserving raw materials through judicious design principles. The designer needs to hew to the principles of these schemes, in the design phase, while leaving room for trade offs

http://dx.doi.org/10.1016/j.heliyon.2017.e00299

arising from parameter-optimization of individual parts and/or assembly of parts into a frugal system.

2.1. Rigorous design process

The padding in *classical* design could be minimized by strictly adhering to the loadings, vibrations and other vital parameters actually seen by a product during its working under real time conditions. In recent years, Rolls Royce Inc (http://www.rolls-royce.com/about/our-technology/enabling-technologies/engine-health-management.aspx#sense) and General Electric (The Economist, 2015) have been using engine-health-management to gather real time data for various critical parameters of jet engines. The loads, mechanical or otherwise, acting on a structure should be monitored real-time to collect long-term data for informing the design process, thereby avoiding extrapolation and also lowering the uncertainty related to load sequence (Boller and Buderath, 2007; Branch, 1976). The design should also be based on models giving accurate predictions; raw materials tested rigorously for their properties and; accurate forecasting of scenarios with a high likelihood of conditions such as overloading during the working of the product. Both predictions and forecasting should be based on well-tested mathematical models giving accurate predictions of critical parameters and stringent statistical analyses of data giving higher confidence levels. In this regard, the latest theories and/or data supporting lower uncertainty should be utilized in the design process. Furthermore, rigor in design should also involve statistically limiting the design parameters to narrow ranges accompanied by high confidence. The standardization-of-parts should be updated for allowing a wider range in sizes, thereby lowering the uncertainty involved in selecting the closest size available for a given component. Even non-standard components, whose fabrication is rendered difficult due to their optimal shapes, should be pursued due to their potential for significant weight reduction (Allwood et al., 2012a).

Overall, a rigorous design procedure would minimize the uncertainties in *classical* design, thereby reducing the *factor of safety*. The lower *factor of safety* above unity – since one reflects working at failure load – would lead to minimal resource consumption that is commensurate to the actual performance of a product in the real world. Therefore, conservative designs in this effort are those that possess *factors of safety* above 1.5. Although this threshold is stringent when compared to the value reported by Otto and Antonsson (1991), its requirement is justified to emphasize both streamlining of design and robust performance for all round *sustainable development*. Other than aircrafts (Torenbeek, 2013; Shanley, 1962; Norton, 2006), where a *factor of safety* of 1.5 is employed to reduce weight, stringent design processes are seldom applied in other sectors, not least, due to the higher costs encountered in their execution.

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The advent of big data and advancement of affordable science and technology (Vincenti, 1990) will eventually bring these rigorous procedures within the easy reach of other sectors. However, frugal products warrant rigorous testing under various scenarios of their usage to avoid failure in critical sectors such as aerospace, healthcare and others having significant bearing on human life. In fact, "frugalization" of critical sectors should be avoided in the absence of rigorous design procedures.

2.2. Alternative design

Designers should envisage "simple" products that can be synthesized with a minimal number of components and/or features for minimizing resource consumption. Apart from these no-frills products, alternative design forms, such as the onionskin model reported recently should also be made avail of. The onionskin model consists of longer lasting components located at the "core" with the "skin" comprising parts requiring frequent upgrades (Allwood et al., 2012b). Such a modular approach facilitates segregation of parts belonging to the core and skin for ease of both upgrades and disassembly (Allwood et al., 2012b). Another alternative design reported recently involves "folding" of components to build products with a high strength to weight ratio (Wood, 2014). Altogether, simple alternative-designs should be considered during the conceptual stage for prospective savings in raw materials when the product is realized.

2.3. Modern manufacturing techniques

Classical design leaves extra material for arriving at specified tolerances and surface finish during the fabrication of a part. In recent years, manufacturing has advanced to the point where a net-shape can be created out of minimal excess material (Linton and Walsh, 2003). Therefore, effective use of existing- and modern-fabrication techniques for skimming lesser material while arriving at the correct shape will lead to significant savings in raw materials. Besides processes, the streamlining of assembly operations has been shown to have a bearing on material savings. This is because products designed through *Design For Assembly* (DFA) typically have lower numbers of parts, connections and complex features to save on assembly time and hence have lower weight due to the concomitant savings in materials (Boothroyd et al., 1994). Accordingly, old- and new-manufacturing processes together with assembly operations should be investigated during the design stage to arrive at a part fabricated out of minimal amounts of raw materials (Boothroyd et al., 1994).

Other than approaching net-shapes, manufacturing processes should also be utilized to impart beneficial features such as ultrafine-grained microstructures and

http://dx.doi.org/10.1016/j.heliyon.2017.e00299

proper sub-surface residual stresses for enhancing product life and hence saving materials (Valiev et al., 2000; Withers, 2007).

2.4. Mimicking nature

The designer should enlist principles of Biomimetics where possible to save on material resources. Biomimetics entails adoption of design principles found in nature to the field of engineering thereby bringing the frugality and efficacy of nature's designs to manmade products (Ball, 2001). Examples include design and fabrication of aircraft wings and wind turbine blades with whale-based tubercles to minimize drag for improved performance with a lower-weight-structure (Bhushan, 2009). The design of the 1972 Olympic stadium in Munich was based on the principle of minimal surface area of membrane structures under surface tension, which translated into economy in weight (Ball, 2009).

2.5. Modern materials

The constraint on design due to dwindling resources could be met by focusing on resources themselves. The use of high-strength materials, including ultrafine-grained (UFG) (Valiev et al., 2000), could result in significant weight reductions vis-à-vis other relatively low strength materials (Allwood et al., 2012a). The principles of Biomimetics should be utilized to create low-weight materials possessing structure varying with scale that confers excellent stiffness and strength to the material concerned (Barthelat, 2007; Wu et al., 2014). Functionally graded materials could also be harnessed for achieving weight reductions in product design (Birman and Byrd, 2007).

Even material testing should be based on samples consuming minimal amounts of raw material. In this regard, the crystalline sponges developed recently (Stallforth and Clardy, 2013) offer the possibility of extracting molecular structures using X-ray crystallography of "nanograms" of sample material.

2.6. Salvaging end-of-life components through 4R mechanisms

In recent years, the cradle-to-cradle concept of sustainability has encouraged remanufacturing of discarded parts and "upcycling" of materials wherein raw materials going into a product are reused after that product's end-of-life (Hoornweg et al., 2013; Bjørn and Hauschild, 2013). The *upcycling* is made possible through melting or any other process that facilitates recovery of major portion of materials going into a product. Therefore, ideally, existing materials such as metals and their alloys could be used endlessly within the same or a different family of products (Wise et al., 2013b). Besides *upcycling* and remanufacturing, organic materials are being created, some of which are edible and others nourish various applications at end-of-life. (Wise et al., 2013b).

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Conventional design principles could be followed for realizing products that are partially/completely built with parts from *end of life* (EOL) systems. An EOL system refers to a product that is past its prime and therefore no longer in use. Therefore, any such EOL system could be disassembled and, ideally, all of its parts utilized in other designs. The EOL parts could be utilized in a new design belonging to the same family or to a distinctly different system but compatible with the specifications of its design. In general, compatibility of parts from an EOL system can be improved by re-manufacturing to facilitate its adaptation to a given product. Besides re-manufacturing, EOL parts can also be salvaged through reuse, recovery and recycling, all of which comprise the 4R mechanisms (Seliger, 2007). The use of EOL systems economizes resource consumption in *classical* design while also adhering to the cradle-to-cradle concept of sustainability. The *End-of-Life Vehicle* (ELV) programs are a case in point, which involve substantial recycling of parts and materials for reuse in the automotive industry and elsewhere (Minter, 2013; Edwards et al., 2006; Seliger, 2007). Reuse of old parts has also been shown to have potential in other industries including construction and household appliances (Allwood et al., 2012c).

3. Theory

A rigorous design would have the *factor of safety* gravitate closer to the unit value (~1.5 – taken from aircraft design, (Shanley, 1962)), thereby minimizing uncertainties and hence resource consumption. Alternatively, a design with an arbitrary *factor of safety* could be realized with materials and parts conserved through any of the schemes, in section 2, save the one on rigorous design. Therefore, improved economization of raw materials could be achieved by taking the *factor of safety* above and closer to one with emphasis on safety and also use as many material-saving schemes as possible.

Accordingly, the *factor of frugality* is a function of both the *factor of safety* and material saving schemes to quantify the thrift in a given design effectively. In other words, the numeric value of the *factor of frugality* would account for the material saved through rigors of *classical* design and, in addition, the material saved through alternative designs, salvaging-4R-mechanisms, modern manufacturing techniques, modern materials, biomimetic design principles and other schemes foreseeable in the future. Hence, the *factor of frugality* (F in F^S) is expressed as a sum of *factor of safety* (S), from *classical* design and, a parameter termed *material saved* (MS) that accounts for raw material conserved through any combination of schemes outlined in sections 2.2 to 2.6. The equations summarizing the proposed *factor of frugality* are given by,

$$F = S + MS \tag{1}$$

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$$S = \frac{S_M}{S_W} \tag{2}$$

$$MS = \sum_{I=1}^{N} MS_I \tag{3}$$

where the first term on the right side of Eq. (1) is the traditional *factor of safety* (S), as given by Eq. (2), which is the ratio between the maximum value of a material property (S_M) and working value of the material property (S_W). Therefore, S_M could be the yield strength (σ_Y) or the critical stress intensity factor (K_C) of the material used in the design and S_W would be the stress (σ) or the stress intensity factor (K), respectively, encountered during the actual working of the design (Shigley and Mischke, 1989). The second term is the *material saved* (MS), which is equal to the total savings realized through all or any combination of schemes outlined in sections 2.2 to 2.6 with MS_I in Eq. (3) denoting the *material saved* in the Ith scheme. Although MS should be calculated from Eq. (3) for new designs, the value of MS is also equal to the difference between F and S due to the relation given by Eq. (1). Therefore, F^S is a symbolic representation that by packing in both F and S for ready reference also serves to readily quantify MS.

The individual components of *material saved*, i.e. MS_I, are listed in Table 1 along with the terminology for their definition. An assumption underlying these

Table 1. Formulations for the components of *MS*. Both the factor of safety and material remain constant in all of the definitions listed below.

No	Scheme	Formulation for *MS component*	$MS_{Maximum}$
1	Alternative Designs (Section 2.2)	$MS_1 = \frac{W_{BULKY\ DESIGN} - W_{ALTERNATIVE\ DESIGN}}{W_{BULKY\ DESIGN}}$	0.5
2	Modern Manufacturing Techniques (Section 2.3)	$MS_2 = \frac{W_{OLD\ PROCESS} - W_{NEW\ PROCESS}}{W_{OLD\ PROCESS}}$	1
3	Mimicking Nature (Section 2.4)	$MS_3 = \frac{W_{TRADITIONAL\ DESIGN} - W_{BIOMIMETIC\ DESIGN}}{W_{TRADITIONAL\ DESIGN}}$	0.5
4	Modern Materials (Section 2.5)	$MS_4 = \frac{W_{LOW\ STRENGTH\ MATERIAL} - W_{HIGH\ STRENGTH\ MATERIAL}}{W_{LOW\ STRENGTH\ MATERIAL}}$	0.5
5	Salvaging through 4R Mechanisms (Section 2.6)	$MS_5 = \frac{W_{SALVEGED}}{W_{TOTAL}}$	1

$W_{ALTERNATIVEDESIGN}$: Weight of the simple or alternative design in Section 2.2.
$W_{BULKYDESIGN}$: Weight of the conventional bulky-design.
$W_{NEWPROCESS}$: Weight of excess material removed by an alternative manufacturing process in Section 2.3.
$W_{OLDPROCESS}$: Weight of excess material removed by a traditional manufacturing process.
$W_{TRADITIONALDESIGN}$: Weight of a bulky conventional design in Section 2.4.
$W_{BIOMIMETICDESIGN}$: Weight of the design realized through principles of Biomimetics.
$W_{LOWSTRENGTHMATERIAL}$: Weight of a design using a low-strength material in Section 2.5.
$W_{HIGHSTRENGTHMATERIAL}$: Weight of a design using a high-strength material.
$W_{SALVAGED}$: Weight of all components salvaged through 4R mechanisms in Section 2.6.
W_{TOTAL}: Weight of the complete product including salvaged components.

http://dx.doi.org/10.1016/j.heliyon.2017.e00299

definitions is that all components except MS_5 have data available from initial design iterations for arriving at their numbers. Another assumption underlying these definitions is that the various *MS* values are computed by comparing designs having the same *factor of safety* and made of same material. The individual contributions to *MS* are defined so as to give an upper value of 0.5 or 1 corresponding to the maximal impact of the scheme concerned. In other words, all components of *MS*, except MS_5 & MS_2, tend to a value of 0.5 as a designer strives to maximize corresponding schemes. As opposed to the 4R mechanisms and manufacturing schemes, where it is possible to conserve 100% and hence take their respective *MS* components to unity, a maximum value of 0.5 has been selected as a conservative estimate for the remaining schemes due to the implausibility of complete conservation. Accordingly, MS_1 of Table 1, which is defined as the quotient of difference in weight between a bulky- and an alternative-design to the weight of the bulky design, tends to a value of 0.5 with decreasing weight of the alternative design. The remaining definitions are similar except for the 4R mechanisms, where $W_{SALVAGED}$ denotes the weight of materials salvaged from EOL systems for a given total weight (W_{TOTAL}) of the product concerned. Therefore, MS_5 approaches unity, as $W_{SALVAGED}$ comprises greater proportions of $\mathrm{W_{TOTAL}}$ with a maximum value of one for a design built completely out of EOL components. It should be noted that material saving schemes and, their *MS* components, not covered in this effort could also be incorporated into the model for F^S through procedures similar to those used in generating the entries of Table 1.

The *safety factor* captures the uncertainty of a given design while *material saved* accounts for the savings realized in opting for efficient scheme(s). For instance, both alternative and bulky versions mentioned in section 2.2 could be designed rigorously with *S* being 1.5 that avoids material padding coming from higher *factors of safety*. However, it is MS_1 that quantifies the extra savings realized by opting for an alternative design, for an *S* of 1.5, with fewer number of parts and hence lesser consumption of raw materials. The same reasoning holds for other components of *MS*, each of which quantifies the savings realized by opting for the concerned scheme at a fixed value of *S*. This arrangement avoids redundancies in accounting for thrift by the components of F^S.

The F^S is a crucial metric that besides controlling design parameters also quantifies the savings achieved in the amounts of raw materials going into a product. A proper value of F^S is dictated by suitable values of its constituents, i.e. *S* and *MS*. Ideally, an *S* in the vicinity of one signifies a design, whose parameters have been determined rigorously with minimal uncertainties. A value of 0.5 for MS_1, MS_3 and MS_4 implies that the corresponding schemes have been utilized to their fullest practical extent. In contrast, a maximum value of one is possible for MS_2 and MS_5 since this would correspond to net shape fabrication without removal of excess material and a product comprising entirely of parts salvaged from EOL systems

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through 4R mechanisms, respectively. Moreover, the approach of individual components of *MS* to a value of 0.5 or 1, for maximal economy, synchronizes with *S*, whose approach to a value close to unity (~1.5) also signifies a thrifty design. Therefore, as depicted in Fig. 1, the maximum value for *F* in F^S, would be the aggregate of a number for *S* slightly higher than one and, an aggregate number coming from totaling the maximum values of the components of *MS*. For example, the maximum value for F^S is $5^{1.5}$ where *F* is 5 when *S* is taken to be 1.5 and maximum values employed for the five *MS* components shown in Fig. 1.

Eqs. (1), (2), (3) and, the definitions of Table 1, is a first generation model for F^S, whose material-saving schemes are easily quantifiable. The model for F^S should be applied to the design of individual components of a product. These individually designed parts will subsequently be assembled into a composite frugal product. This effort stops short of quantifying other aspects of *MS* such as material saved over the longer term by imparting apt textures and residual stresses through suitable manufacturing processes. More of these subtle savings in materials through relevant schemes should be characterized in futuristic efforts.

4. Calculation

4.1. Computing the factor of frugality

The efficacy of F^S in quantifying frugality of material consumption is brought out by the hypothetical cases of Table 2. It should be noted that all cases, except 3, use a *MS* value of 3.5 based on maximum values of components shown in Fig. 1. Case

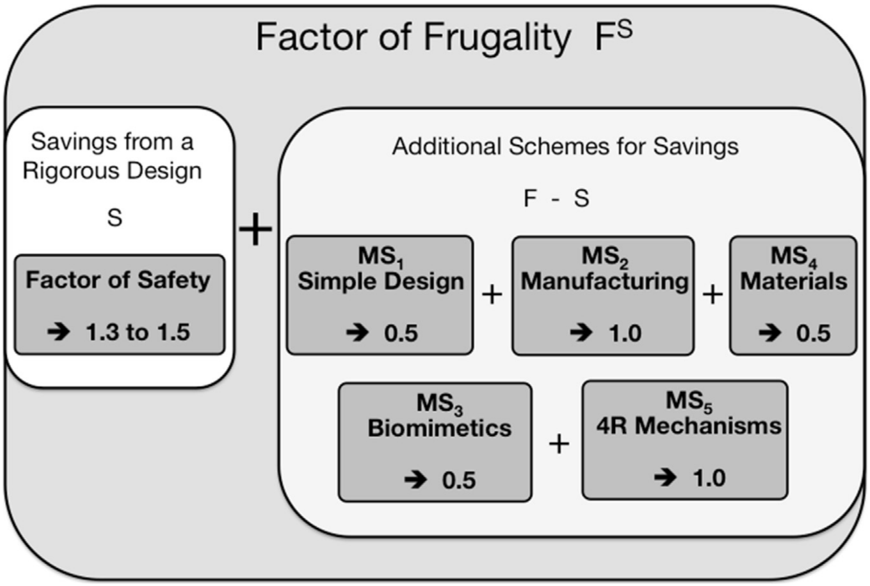

Fig. 1. Schematic for an optimal factor of frugality. Arrows signify approach of components to their maximal values.

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Table 2. Efficacy of the *factor of frugality*. (The numbers listed in this Table are not specific to any real time cases. These numbers have been created for expounding the workings of the *factor of frugality*. Maximum values of 1 and 0.5 have been assumed for MS_2 & MS_5 and MS_1, MS_3 & MS_4, respectively. For case 3 a maximum value of 0.5 has been assumed for each of the five extra components of *MS*.).

No	Factor of frugality F^S	Factor of safety S	No of material saving schemes	Material saved MS $(F - S)$
1	7.5^4	4	5	3.5
2	$4.8^{1.3}$	1.3	5	3.5
3	$7.3^{1.3}$	1.3	10	6
4	4^4	4	0	0

3 uses five extra arbitrary schemes with each additional scheme contributing a maximum value of 0.5, which takes the *MS* value from 3.5 to 6.

The higher the difference $F - S$ the higher the amount of material saved through frugal schemes in excess of savings coming from a given *S*. This is borne out by cases 2 and 3 of Table 2, whose extra savings through *MS*, correspond to values of 3.5 and 6 respectively, for an *S* value of 1.3. Although cases 1 and 2 have identical *MS* values for different values of *S*, i.e., 4 and 1.3 respectively, the total savings is optimal only for case 2. Even though case 1 has a higher *F* value, it has an *S* value of 4 that indicates higher uncertainty and hence more material wastage vis-à-vis the S value of 1.3 in case 2. Case 3 also highlights the potential for higher *MS* and hence a higher *F* number through additional arbitrary schemes realizable in future. The absence of any material saving schemes in case 4 makes the *factor of frugality* same as *factor of safety*. It should be noted that bulk of current designs following the *classical* approach are typified by case 4. Therefore, just following suitable material saving schemes would improve the *MS* and hence *F* numbers for these designs until further improvement in *F* is sought through the realization of tighter *S* values − whose realization could be abetted through advances in big-data and also progress-in-technology.

4.2. Example: frugal design of a shaft

An example on design of a shaft, as reported by Urugal (2015), has been selected in this study for exemplifying the proposed *factor-of-frugality*. The focus on shaft is justified by its significance as one of the fundamental elements in mechanical-design that is widely used in applications requiring transmission of power and/or conversion of motion from linear to rotary and vice versa.

Table 3 lists results from both *classical* design, taken as the baseline for comparison and, the frugality approach- implemented through three of the schemes outlined in section 2 − for a shaft made of steel transmitting 500 kW of power at

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Table 3. Frugal design of a shaft. Material is Steel (Shear strength = 300 MPa & Shear modulus = 80 GPa) Power transmitted = 500 kW, Rotational speed = 1200 rpm, Factor of safety = 1.5.

	Approach	*S*	Conservation Schemes			F^S	Outcome
			MS_1	MS_2	MS_5		
1	Classical (Basic)	1.5	-	-	-	$1.5^{1.5}$	Solid Shaft
2	Frugal	1.5	0.5	-	-	$2^{1.5}$	Hollow Shaft
3	Frugal	1.5	0.5	1	-	$3^{1.5}$	Tube Extrusion
4	Frugal	1.5	0.5	1	1	$4^{1.5}$	Salvage Extruded Tube

1200 rpm. A *factor of safety* of 1.5 and relevant values for the strength and shear modulus of steel have been selected from Urugal (2015). The diameters reported here and, also listed in Table 3, are rounded to the nearest whole number for clarity. The first entry in Table 3, corresponding to baseline design, lists a solid steel shaft of diameter (*D*) of 46 mm that satisfies requirements of pure torsion during power transmission. The remaining entries pertain to frugality approach with the second entry on alternative designs (section 2.2) listing equivalent results for a hollow shaft, whose outside diameter (*D*) is 1.25 times the inside diameter (*d*). This results in a weight reduction of 50%, or MS_1 value of 0.5, which is reflected in the F^S value of $2^{1.5}$. The third entry refers to the use of a suitable manufacturing technique for producing the hollow shaft. The production of hollow shaft by indirect extrusion, as opposed to machining, results in an MS_2 of 1 as computed from entry 2 of Table 1. This value of MS_2 reflects significant savings from not having to machine the internal diameter out of a solid shaft, while taking insignificant finishing cuts on the inside and outside surfaces of both the extruded- and machined-shaft. The final entry lists the salvaging of such an extruded hollow shaft from an EOL system and accordingly adds 1, or $MS_5 = 1$ (obtained from entry 5 of Table 1), to the *factor of frugality*. Fig. 2 illustrates the various outcomes at different stages of the frugal-design process listed in Table 3.

Each of the individual material saving schemes adds up to give a *factor of frugality* of 4 with the representation of $4^{1.5}$. The *classical* approach yields a baseline design with an F^S value of $1.5^{1.5}$. In other words, the baseline design conserves material by adhering to a factor of safety of 1.5 without involving any of the additional conservation schemes. In contrast, each of the other schemes based on an alternative design, manufacturing and salvaging, respectively, lead to a cumulative improvement of the *F* value by 167%. This improvement in the *factor of frugality* attests to its significant potential for quantifying conservation of material resources and hence making the *classical factor of safety* stronger.

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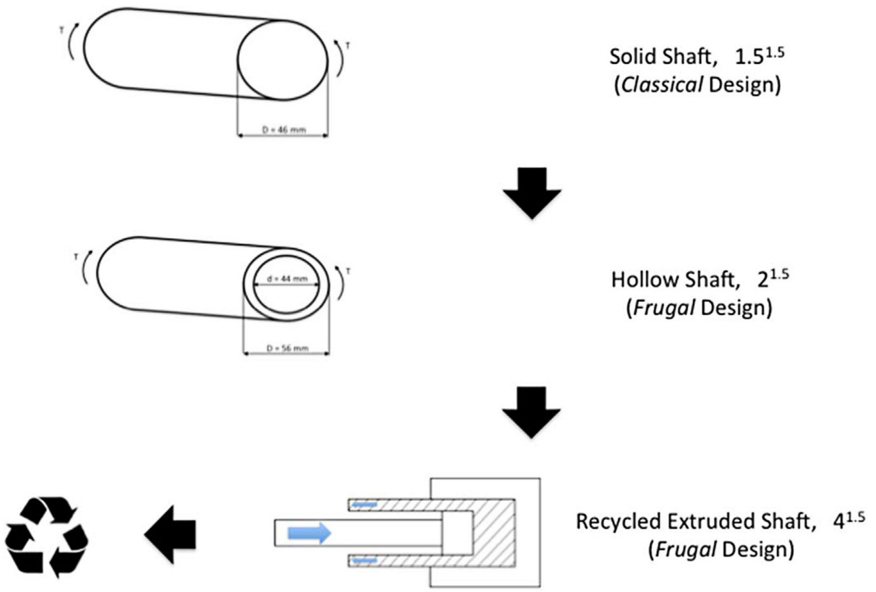

Fig. 2. Outcomes in the frugal design of a shaft. F^S values show the accompanying improvement in frugality.

Other elements of mechanical design such as plates, gears, beams, springs etc. can also be similarly designed and fabricated for frugality. These individual frugal elements will get assembled into a composite whole to form a given frugal-product.

5. Discussion

The *factor of frugality* can also be applied inversely in the conceptual stage to simulate a proper mix of safe-and-rigorous-design and material saving mechanisms. The variation in F of F^S and its components should be thoroughly studied in the initial design stage, prior to fabrication, for realizing optimal savings in materials. Although S is subsumed in F^S, it will continue its role of making products both functionally robust and safe by presenting itself in the relevant formulas of engineering design. Since design is an iterative process, the *factor of frugality* and its constituents, in some cases, will have to be evaluated in finite iterations when weak spots are revealed during initial design cycles.

The *factor of frugality* would also aid in assessing the impact of a design on global-warming. An optimal value of F^S would signify judicious use of raw materials that generally translates (Moynihan and Allwood, 2014) into lower GHG emissions. Therefore, frugality in resource consumption might also lead to a product, whose realization is a net saver of energy with a positive impact on climate-change. However, a given design should be scrutinized for hotspots in its cradle-to-grave cycle, such as raw material extraction and disassembly, which could exhale larger amounts of GHGs and thus make the design a net emitter. Therefore, values of F^S

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could be scrutinized in tandem with relevant results from the *Life-Cycle-Analysis* (LCA). Such a combined study will aid in concluding definitively about the emission credentials of a given design. In fact, a single number from LCA could be appended to the *factor of frugality*, as in F^S_{LCA}, in a futuristic effort. Consequently, maximizing *factor of frugality* while sticking to the rigors of design could lead to better products that are environmentally benign. Therefore, adoption of F^S would revamp the *classical* design process and usher in a philosophy based on designing-for-frugality that stresses performance and economy in material utilization.

The *factor of frugality* is also an apt measure of eco-efficiency for all-round *sustainable development*. The focus on economizing usage of raw materials aligns with the premise underlying eco-efficiency, i.e., minimize wastage (Montgomery, 1997). In fact, products could be showcased for their frugality by displaying F^S values on their labels. A higher value for $F - S$ together with a suitable S would signify optimal savings in raw materials. In this regard, standardizing the procedure for evaluating F^S, including number of *MS* schemes and their maximal values, would facilitate comparison of F^S between products.

The close proximity between manufacturing and design is crucial for innovations (MIT, 2013). In fact, exodus of many manufacturing facilities offshore has disrupted this proximity thereby impairing developed countries from harnessing manufacturing for lucrative innovations. In this regard, use of F^S, which explicitly accounts for both materials and manufacturing through *MS*, would facilitate quantification of improvements in design through schemes such as modern-manufacturing thereby encouraging product-development-activities under one roof for innovating effectively in a globalized economy. Last but not least, F^S could be employed for both the systematic design of *frugal-innovations,* which have become popular in recent years (Rao, 2013) and, the study of their dynamics of interdependencies. In particular, use of F^S values as proxies for multitudes of *frugal-innovations* could aid network studies seeking to bring out any instabilities arising from overcrowding of these innovations (Hellmann et al., 2016; Helbing, 2013).

6. Conclusions

The philosophical underpinnings of a new *factor of safety* for tracking both safety and frugality in the ecodesign of a product, with a first generation model, have been presented in this work. The *factor of frugality* (F) subsumes the classical *factor of safety* (S) widely prevalent in engineering design. The representation F^S, for the new factor, teases apart contributions from both a rigorous design process (S) and various additional material saving schemes ($F - S$) to bring out the environmental credentials of a given product. The increasing value of the *factor of frugality* beyond 1.5, against a maximum of 5, signifies increasing savings in the

http://dx.doi.org/10.1016/j.heliyon.2017.e00299

resources consumed by a given product designed rigorously with a *factor of safety* of 1.5. An example on frugal shaft design has shown the potential to conserve material through a rigorous alternative design that is realized by salvaging an extruded hollow shaft from an EOL system. Even without a tighter *safety factor*, the use of material saving schemes built into the *factor of frugality* would result in realization of products with lesser wastage of raw materials. Other than quantifying the rigor in product-design and also savings in raw materials, F^S can be used as a measure of eco-efficiency and proxy for network studies related to overcrowding of *frugal-innovations*, to name a few of its applications. The *factor of frugality* can be applied to various industrial sectors, including aerospace or healthcare, after accounting for their specific constraints and complexity of design. These distinct sectors will get tuned to the rigor and frugality of the approach with time. The use of the *factor of frugality* from here onwards could upend *classical* design philosophy and create products that are in sync with principles and policies for mitigating the impacts of climate-change and resource scarcity.

Declarations

Author contribution statement

Balkrishna Rao: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The author declares no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The author is grateful to the *Rural Technology Action Group* (RuTAG), at the *Indian Institute of Technology Madras*, for their inspiration underlying some of the concepts of this research effort.

http://dx.doi.org/10.1016/j.heliyon.2017.e00299

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