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Durability as a techno-socio-economic concept

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Abstract

While the "useful life" of products plays an important role in the balance of sustainability and lifecycle assessment, the concept of durability, as the main measure of useful life, is still ill-defined. This paper critically considers the limitations of the current definitions and approaches to durability, by reflecting on the complex interactions of the viewpoints of engineering design teams, users, society and business economics. A new definition is proposed for durability relating to the useful life goals for a product within its techno-socio-economic context.

Keywords: sustainable design, circular economy, durability, reliability

1. Introduction

The increased focus on sustainability and circularity across the manufacturing industries has brought wide recognition of the benefits of designing and developing systems that are durable, robust, dependable and resilient in providing their function throughout the intended lifetime. Circular economy considers options for the end of the useful life of a product (i.e. recycle, reuse, remanufacturing), with the focus now shifting towards designing for longer useful lives (i.e. higher durability) for enhanced sustainability (Messa et al, 2022). Extending the life could provide higher product value, better use of resources, and opportunities for higher value re-use or re-purposing of durable parts at the end of life.
From a technical point of view durability is concerned with proving that the design life of a physical product is achieved under the specified mission profile. Thus, durability is closely with the reliability and robustness (Eifler et al, 2023). The economics of durability largely focusses on trade-off between the design life of the product (which has a significant bearing on the cost) and the value achieved from its exploitation, often based on marginal costing (Saleh, 2008). For repairable systems this includes the cost of repair and maintenance, or a measure of the lifecycle cost (Cappelletti et al, 2023). Recent efforts to derive durability indices aim to enable comparisons between products (Habibollahi et al, 2023).
This approach to durability is effective in relation to industrial or infrastructure systems, typically maintained as assets. However, for consumer goods, the expectations, perceptions, behaviours and attitudes of the consumers can have a significant impact on the actual durability of the systems. This not only means higher uncertainty around how the product is used (which could include use cases the design team had not envisaged, or even abuse), but also in relation to their attitudes to repair a faulty product (sometimes referred to as *technological obsolescence*), or the decision to discard a still functional product based on their subjective perception of performance, including non-functional characteristics like aesthetics, i.e. *functional* and *psychological obsolescence* (Woidaski & Cetinkaya, 2021). The social influence on the preferences for durability of different products has also been widely discussed in literature (e.g. Dobeson & Kohl, 2020).
The proliferation of smart features, with functionality defined by software, has also brought new complexities to durability. The useful life is determined by both the performance of smart features and

the degradation of the physical part of the product (e.g. consumers lose trust in the product and decide to discard rather than repair). Furthermore, obsolescence is now often linked to software functionality rather than the hardware, leading to the shorter durability. In certain conditions, designed obsolescence is regarded as unacceptable, even referred to as "corporate environmental crime" (Bisschop et al, 2022). This conceptual paper draws from the extensive experience of the authors in complementary industrial fields and proposes a comprehensive argument that durability should be considered as a construct with technical, social and economic dimensions, which requires a holistic consideration in order to enable effective approaches to enhance the sustainability of the products by design and through life. We introduce, as novel contribution, a goal centric definition of durability, to reflect the intentions and goals of both users and product designers. Based on this definition we carry out a broad analysis of the prevalent engineering trade-offs and social and economic implications. The paper is based the authors long standing experience of working on safety and reliability as well as engineering change and their ongoing engagement with the unfolding research literature.

2. On definitions of durability

Depending on the viewpoint, durability is often thought of in different terms, reflected in this section. *Intended life* or *design life* consider durability from the perspective of the product designers and developers, whereas *useful life* reflects a user perspective.

2.1. Critical review of existing definitions of durability

The traditional technical definition of durability refers to "the ability of an entity to remain able to perform a required function under specified conditions of use and maintenance, until a limiting state is reached" (Villemeur, 1992). This definition builds on the earlier fundamental work to characterise the effect of the gradual degradation processes (e.g. wear) on mechanical components, to derive *durability* models that predict the life in relation to the machine operating conditions (Pronikov, 1973). This definition, almost unchanged, can still be found in contemporary standards, such as the EN45552 (2020). In more general terms, durability is defined as "a measure of *useful life* (a special case of reliability)" (MIL-STD-721C, 1981). This definition is useful because it clearly sets durability as a key metric in the context of the product lifecycle, referring to the "useful life" of a product or system. MIL-STD-721C (1981) also relates explicitly durability to reliability, which refers to "the ability of an item to perform its intended function for a specified interval under stated conditions". For a non-repairable item, durability and reliability are intrinsically linked, in the sense that reliability will measure the probability of achieving the stated useful life set by design, whereas durability will quantify the life achieved by a set percentile of the population. For repairable items, durability also depends on the ability to repair the item upon failure, until the limiting state when the failed item is beyond repair is reached, i.e. the end of useful life. Cooper (1994) has introduced a definition of durability that reflects the impact of maintenance and repair, i.e. "*ability* of a product to perform its *required function* over a *lengthy period* under *normal conditions of use* without *excessive expenditure on maintenance or repair*". This definition is still commonly used (with small adaptations) in current research (e.g. Cappelletti et al, 2023).
In an engineering context, referring to infrastructure technical systems or equipment, regarded and maintained as assets, the operationalisation of this definition is relatively straightforward, as it revolves around identifying the key characteristics (usually related to failure mechanisms) in terms of which the "*limiting condition*" for durability will be defined, following the lifetime operation of the equipment in "*normal conditions*", i.e. either controlled or monitored. Failure (of the required function) is defined in technical terms in relation to the input / output conditions or attributes, which are normally monitored to diagnose current operating state and predict the *remaining useful life* (RUL). Decisions on the "*end of useful life*" are made based on the joint consideration of the expected remaining useful life metric (either probabilistic or RUL) and the expected cost of maintenance and repair (Cappelletti, 2023).
However, in relation to consumer products, the terms highlighted in Cooper's definition above ("*ability*"; "*required function*"; "*lengthy period*"; "*normal conditions of use*"; "*excessive expenditure on maintenance and repair*") could all have connotations of ambiguity, as they are subject to the *interpretation*, *judgements* and *actions* of users. This can be argued both *inductively* (on the basis of considering empirical examples of consumer products, e.g. cars, mobile phones, laptops, clothing, etc)

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and *deductively*, based on the theoretical foundations for the definitions of *failure*. To give a brief illustration of the former, consider the case of a mobile phone:

- The *ability to perform the required function* (e.g. make a call, browse the internet, take quality pictures) is often subject to user judgement, who could deem the product unable to deliver the function as expected, even though there is no clear device fault present. In relation to the way the user interacts with the product, the threshold for failure cannot be crisply defined, and it is best described as a fuzzy concept, as illustrated in Figure 1. E.g. the time to establish a connection for a call (which is subject to extrinsic factors such geolocation, weather and network performance, as well as intrinsic device-related condition or state) could be deemed either acceptable or unacceptable by different users in the same use case scenario, or the same user could deem it acceptable in some use cases and unacceptable in others (e.g. placing an emergency call). This also means that the operationalisation of the concept of "*limiting state*" referred to by the classic definition of durability, is dependent on the user judgement of the ability to perform the required function; if this is deemed inadequate (with or without a physical fault of the device), the device would have reached the end of useful life. Figure 1 illustrates that the subjective user-defined failure zone could have a trend, where users could be more tolerant with product performance as the product ages. A key message from this analysis is that the variability of the observed durability is amplified by the subjective behaviour of the user.
- The expectation for the length of useful life (or how long should the "*lengthy period*" be such that it is deemed satisfactory) is also subject to the judgement of the user. In turn, this is dependent on several subjective factors, like preference for keeping up-to-date with fashion and technology (in which case the length of useful life would not be a primary criterion, and the product might be discarded prematurely, without any fault), or emotional attachment to a particular product (in which case the length of useful life is important, and users will seek to extend the useful life of a product). The economic context is also important, favouring longer useful life expectation where affordability to replace is an important factor.
- The "*normal conditions of use*" is also uncertain, often difficult to define at the design stage or as part of a usage contract for many consumer products. Even a cursory web search of issues with a specific mobile phone would reveal failures occurring in perfectly normal usage conditions that have not been envisaged in the requirements capture and product testing stages (e.g. the famous failure of the i-phone when inserted in a tight jean pocket). Furthermore, the users will often identify new affordances (Maier & Fadel, 2009) or uses for the device in otherwise regular circumstances, thus extending the manifold of normal conditions of use.
- The user ultimately decides what is "*excessive expenditure on maintenance and repair*". This depends on the user attitudes towards repair and mending, as well as availability of repair options and cost / affordability of repair versus replacement.

This analysis clearly outlines the insufficiency of the current definitions of durability, and argues the need to consider concurrently the technical, social and economic considerations in defining durability.

2.2. Proposed goal-centric definition of durability

Based on the analysis of the definitions, durability of a product is associated with the concept of failure. Failure is typically defined as the "termination of the ability of an item to perform a required function" (IEC, 1990). Engineers tend to focus on the phenomenology of the technical failures, with function failures defined in relation to the specifications required, caused by material failures, defects, faults and errors (Yellmann, 1999), considered independently of customer perception. However, as discussed in the previous section and illustrated in Figure 1, across the product lifecycle, engineers are likely to see user determined failure events not limited to the ability to perform the specified duty. This prompts for the need to consider the definitions of function and failure in a much broader sense.

Building on the user- and use-case centric function reasoning originating from software engineering (Cockburn, 2000), and the description of functions from either a device-centric or an environment centric viewpoint (Brown and Blessing, 2005), Vermaas (2009, 2013) has introduced an ontological framework that includes *goals*, *actions*, *functions*, *behaviours* and *structure*. This offers an opportunity

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to consider the concept of failure in relation to stakeholder goals, and not just in relation to structure and specifications of functions / behaviours as the prevalent engineering approach. In this vein, Del Frate (2013) poses failure in terms of *goals* rather than function, with product failure defined as "*the inability of an engineering process, product, service or system to meet the design team's goals for which it has been developed*". This definition is structurally similar to the conventional definition of failure as a form of inability of the product, however, failure is referred to the "goals of the design team" rather than a specific required function. For del Frate (2013) this is a negotiated and agreed set of goals of stakeholders beyond a single organisation; and includes the satisfaction of the users.

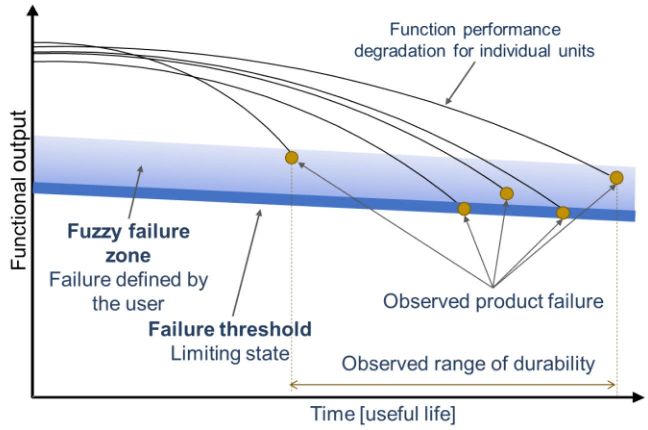

Figure 1. Durability in relation to subjective user defined failure threshold

Projecting this perspective on considerations for the definition of durability, we firstly reflect that the current definitions are unduly centred on the device-centric view, with insufficient and imprecise consideration of the other views. A more comprehensive definition of the concept should reflect the whole spectrum of goals, i.e. user-, environment- and device-centric, as outlined below:

- *User-centric goals* regarding durability reflect, beyond the immediate intent on functionality related to an activity or task, the user attachment to the product (subjective / emotional utility), the attitude towards repair and mending, and the affordability position throughout life. For products with longer lifetimes, the user goals might evolve through the lifecycle of the product.
- *Environment-centric goals* for durability reflect the prevalent societal values, including environmental and socio-economic sustainability goals, societal values and social and fashion trends (which are not always congruent with other environment-centric goals, but nonetheless an essential component of the societal sustainability).
- *Device-centric durability goals* for the product reflect the choices and decisions of the *design and development* team, informed by their assessment of the user- and environment-centric goals, pertinent to the target user group and the envisaged usage scenarios and profiles. This should include, inter alia: performance goals defined for the expected design lifetime (as intended useful life of the product), including the reliability / repairability / maintainability goals; it should also consider goals for the product end-of-life *residual value* for recycle / reuse / upcycle; as well as other environmental sustainability goals (e.g. lifecycle carbon emissions) which could be set at or above the regulatory compliance level.

Integrating these viewpoints, we propose a new definition of ***durability*** as ***the ability of a product or system to meet the intended useful life goals of the users and the design team***. While structurally similar to other definitions, the proposed anchors durability in the frame provided by integration of the (socially conditioned) goals of the users in relation to the useful product life, with the goals of the design and development team, capturing their intent for the whole product lifecycle performance and management, which encapsulate requirements derived from the environment-centric considerations. This broader definition allows engineers to reason more comprehensively about durability, beyond the immediate functional-related context of the current definitions, including reflection on a system of goals from which both functional and non-functional requirements can be meaningfully derived.

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3. Engineering trade-offs when considering of durability

In order to establish a concept for durability for a specific product, including goals and specifications, the design team needs to navigate the complexity of trading off goals, values and requirements within a complex mix of stakeholders. Such trade-offs are often difficult to trace and quite involved. In this section we discuss some of the key engineering trade-offs associated with durability, with arguments and examples drawn from the extensive experience of the authors across a wide range of industry fields.

3.1. Extended design life vs product and technology innovation

Having consumer products (e.g. mobile phones) with shorter design life (i.e. less durable) has been seen as beneficial for innovation, as feedback from customers is used to enhance the design of the product, bringing to market better products faster. The problem with this approach is that it can have a significant environmental impact, exacerbated by the poor recycling statistics of electronics (Koulompis et al, 2023). However, designing systems with extended lifetimes is not necessarily better from a sustainability point of view; this is because the energy efficiency of products can deteriorate over time, while new products equipped with updated technologies, would offer a much better efficiency, as illustrated by Bakker et al (2014) in relation to fridges and laptops.

Obsolescence in product design is closely related to the consideration of the interplay between durability and innovation, with new technologies replacing older, less efficient or performant products. However, for new generation of consumer products where software defined functionality plays a significant role, software-defined obsolescence has often forced premature hardware upgrade (e.g. as it is the case with mobile phones), without full consideration of environmental sustainability.

3.2. Actual vs perceived durability

From an engineering point of view, the unit of life for a product is typically measured in load or usage cycles, and the useful life equates to the cumulative count of usage cycles (e.g. the life of aircraft tyres is measured in the number of landing events). More specific to durability predictions, we are interested in the key characteristics associated with the failure mode either instantly or over time, as a result of the *damage* accumulated with every usage cycle. However, from a user point of view, the reference to usage cycles is not useful in relation to measuring the useful product life, even when the count of the usage cycle is relatively straightforward, e.g. the number of journeys with a car. Instead, for the user convenience, design life of products it typically expressed in units of time, most commonly years; e.g. design lifetime of a car is (typically) 10 years. The designers will use information about the typical user duty cycles to establish corresponding targets in units that are more closely related to the load cycles; e.g. 250,000km; 7,000 vehicle starts; 1,000 BEV battery charges. Consistent communication with the users can address this gap; e.g. most motorists will refer to the mileage of their car as indication of life, as well as years. However, this is not common across consumer products. For example, the design life of lightbulbs is quoted in hours, e.g. 25,000 hours. While this is a useful metric to compare between products on offer, it is not a useful metric for a user since the hours of usage are not monitored. Even if users would work out that 25,000 hours would equate to a lightbulb life expectancy of about 12 years of moderately high usage, this is unlikely to be useful as very few users would record or recall when they fitted the new bulb. It is also the case that many users will be unable to use a lightbulb for 12 years. This discrepancy is further exacerbated if the actual technical characteristic associated with failure is considered. E.g. for a classic lightbulb the dominant failure mode is associated with the switch-on events; therefore, counting life in number of events will be a lot more relevant. Some users will feel disappointed with the observed life (measured in years) of units subjected to frequent switch on events. Similar paradigm exists for many other consumer products; for example, power tools targeted at DIY users have a target life limited to tens of hours; for the occasional DIY user this could mean many years of service; however, a moderate user would likely experience a much shorter useful life expressed in years. While this might result in large variability in the observed / perceived useful life, from the engineering point of view, it might still be consistent in terms of the relevant damage metrics, if the product is used until the technical failure.

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Therefore, identifying distinct usage profiles is important to identify the intended target user group for the product. This facilitates the setting of engineering design life targets aligned with the user goals and perception, and correlated with the key characteristics related to damage. Complications often arise from the fact that even simple products have multiple functional requirements, therefore, useful life is defined by the interplay of competing failure modes or mechanisms. For example, a fully functioning device might be deemed unusable if it has the aesthetics appearance of an old / worn out product.
The durability design target will have a significant influence on the technology and materials choices for the device, which will also be reflected in the cost / price point of the product.

3.3. Durability of system vs durability of modules

While products with relatively simple structure are expected to be recycled at the end of useful life, for complex systems the design team goals for durability depends on the level of responsibility in relation to the system integration. Referring to a well-known example, the durability of an aero engine will be considered in its own right separately from the durability of the aircraft system-of-systems. An aircraft will likely be serviced by several engines over its lifetime, whereas and aero engine will service several aircrafts during its useful lifetime. In general, modules (subsystems) or components can survive the system, and can continue life in another system through reuse, with or without being *refurbished* or *remanufactured*. In some cases, the whole system can be *refurbished* or *remanufactured*, where new or re-used components replace failed or worn-out components. Modules of components can also be *upcycled* where they are repurposed for use in completely different systems. For example, BEVs (battery electric vehicles) are currently designed to be serviced by several battery packs over the expected vehicle life. The battery pack systems (e.g. including the cooling system) can be designed to be *repaired* or *refurbished* (or *remanufactured*), and fitted to the same vehicle or to another vehicle as a service pack. The battery packs can also be designed to be *upcycled* in stationary power banks. The interplay between the goals of the OEM design team as systems integrators, seeking to optimise the durability of their system, and the goals of the module designers, who seek to optimise the value of their product through extended lifecycles (where the module durability is the manifold of multiple lifecycles), is defining the increased complexity of lifecycle management within a systems of systems context.

3.4. Soft failures vs hard failures

The traditional approach to design for durability of components was largely focussed on dealing with physical systems, centred on the physics-of-failure (*p-o-f*) approach to characterise the phenomenology of failure modes, and stochastic models of damage accumulation to predict failure. Testing activities in product development focussed on one hand on characterising materials behaviour to underpin the *p-o-f* models, and on the other hand to verify the target durability life against a load profile representative of or correlated with the real world customer usage, with statistical-based performance metrics (Salzman & Ciemniecki, 1997). While material and component testing for durability / reliability is well established, in many cases with reference standard testing procedures and methodologies, this very much remains an active area of interest given the advent of new technologies and new materials that need to be characterised (Campean et al, 2020). However, as consumer products have become more complex, both in terms of their physical structure and the proliferation of embedded electronics and software in system architectures, the phenomenology of failure modes associated with the system durability has diversified to include both "*hard failures*" and "*soft failures*" (Clausing & Frey, 2004). This has triggered a swift shift towards *robustness* and *robust design*, as the relationship between robustness failure modes and the performance indicators associated with useful life (e.g. cost of repair and maintenance, reputation, safety and durability) has been very quickly realised. This is very much an evolving research challenge (Campean et al, 2020), in particular given the current proliferation of embedded AI, which brings new, hitherto unexplored, complexity for robustness and durability.

3.5. Durability vs other DesignX considerations

Taking a broader perspective to the context of product design, including the environmental goals of the design team, optimisation of durability needs to consider the design for "Re-X" (Pigosso et al, 2010),

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e.g. design for repair, recycling, remanufacturing, aso. The interplay between objectives and performance within this set of objectives and options is often not straightforward, and seldom considered holistically. For example, the design of smart watches has become increasingly robust to noise factors such as humidity and water ingress; while this extends the performance characteristics and useful life of the device, it makes repair (e.g. to replace the battery or broken glass) more difficult. While making the device easier to repair, including by the users - as requested by the right to repair movement, is predicated upon the expectation of extended the useful life (Saidani et al, 2023), but this might come to the detriment of the reliability and robustness of the new product. Thus, there is a trade-off between robustness and repairability at a given level of technology and cost, and the implication of the choice of an optimal solution at the design stage needs to consider holistically all the objectives within a lifecycle cost analysis. This is often very difficult to assess at the design stage, given that it depends on the actual behaviours of the users and other stakeholders, which are not always known ex-ante (e.g. even with skilled repairers the outcome in terms of the expected life after repair can be highly variable).
For infrastructure industries (nuclear, aerospace, and even manufacturing) this complexity is handled via the use of standardisation to reduce uncertainty. However, this often limits the scope for environment-centric durability optimisation, e.g. via the use of refurbished or remanufactured modules, as certification for the performance of such components is generally not available.

3.6. Designed durability vs active system health management

While the use of maintenance and repair to extend the useful life of a system have been known and used for a long time, the availability of sensors and technologies to monitor the products and systems in the real world and increasingly in real time has opened up radical new opportunities for integrated *systems health management (ISHM)*. E.g., the JA6268 (SAE International, 2018) aerospace and automotive recommended practice (applicable to other systems) provides a six-levels reference framework for health management capability, with "self-adaptive health management".
ISHM has a significant potential for enhancing the useful life of systems, by several mechanisms:

- Continuous monitoring of systems and modules, centred on failure modes and mechanisms, for on-line diagnostics and prognostics with optimal corrective action. This avoids the risk of catastrophic failure with significant damage to the system, while early preventive action will minimise the damaging effect on other components / parts of the system.
- Early intervention is also known to enhance the user experience by avoiding downtime; with software defined functionality, it is also possible to fix failures without the user knowledge. This potentially influences the user attitude towards keeping the product in use for longer.
- The availability of diagnostics and prognostics also has the potential to enhance communication with the users (e.g. providing an indication of the remaining useful life), which is important in building trust in the system, with potential impact on attitudes towards durability.
- Within a system of systems (SoS) context, communication of remaining useful life between systems or modules, underpins a proactive approach to safety and dependability management (Campean et al, 2021), with positive impact on resilience and useful life.

However, ISHM further increases the complexity of the system, with potential detrimental impact. E.g., the introduction of online emissions monitoring devices in vehicles has resulted in unavailability due to faults of the monitoring system, rather than the system itself, with negative impact on user perception.

4. Impact of socio-economic constructs on durability

Dobeson & Kohl (2020) have introduced the concept of "*socially expected durability*", explaining that "*how long a good is expected to persist through time is not simply a question of its physical features, but also of how we manipulate it socio-technically and what cultures and norms of use exist at a given point in time*". This confirms the importance of the interplay between technology, dynamics of societal trends and expectations inter-related with technology evolution (e.g. features of performance of personal electronic devices as elements of fashion), and the enforced norms and regulations (e.g. environmental or safety legislation), with significant impact on durability.

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In this paper, taking the prevalent view of consumer products, we have discussed several examples of direct impact of the user perceptions, behaviours and attitudes on the actual durability as observed useful life. We have illustrated the detrimental impact on durability in some cases, e.g.:

- The subjective perception of functional performance, either related to relative degradation in performance of existing product, or revised desirability of feature linked to technology advancement (e.g. new products offering new features and better performance);
- Attitude towards failure and repair: experience of failure (even soft failures) can be perceived as poor performance or could affect the user confidence in the product, resulting in the product been discarded from use even if it could be mended or repaired.

On the other hand, durability extending attitudes can be observed, e.g.:

- Personal attachment to a product would drive individuals to keep products for longer, even with a reduced usage rate or alongside a new device;
- Cultural background favouring an inclination towards keeping the products for longer, and a positive or even proactive attitude towards repair and mending to extend product life.

A deeper understanding of the relationship between durability and the user perceptions, behaviours and attitudes, in particular those related to the new technologies (intelligent systems with embedded AI features), requires further exploration and research.

The cost of durability is generally thought to be well understood. Saleh (2008) has provided an excellent critical discussion of the common approach based on the marginal costs of durability (e.g. cost per day or cost per payload), and has introduced an analytical framework based on the *net present value*, which considers the dynamic context in which the system operates. Based on the consideration of the broader context of the product whole life cycle costing, Cappeletti et al (2023) have introduced a cost-based framework and tool for durability optimisation at design stage for energy related products.

However, the argument emerging from the discussion in this paper is that a more realistic accounting framework for durability is needed to reflect all pathways of the actual useful life of a product. Figure 2 provides an illustration of the product lifecycle pathways from a product / component durability perspective, illustrating ramifications beyond the conventional onion-shaped representation of circularity pathways. This analysis prompts several points of reflection:

- There is significant variability in the actual / observed useful life (i.e. durability) of products, dependent on the users behaviours; this requires a data driven approach to evaluate uncertainty and establish realistic predictive models at the design stage;
- Both cost-based durability optimisation at the design time and the net present value approach used in operation, should consider appropriately the value at the end of useful life for both the system and subsystems / modules. There is significant potential value embedded in modules of complex systems at the end of life, unlocked through reuse and upcycle. This could be optimised through design, which means that the optimal design strategy should consider concurrently the durability of the modules and that of the systems, to optimise value;
- Durability optimisation should also consider an optimal level of sensors and AI for effective *ISHM* to extend useful life, with potentially reduced costs of maintenance and repair. As the evidence for the benefits of such technologies is still emerging, it is difficult to prescribe the approach to cost-benefit trade-off.

The opportunities afforded by the holistic consideration of durability in a socio-technic context pave the way for potentially significant service and business innovation.

5. Discussion and conclusions

This paper has provided a comprehensive argument for the positioning of durability as a construct within the social, technical and economic domains. The traditional approach of optimising durability at the design stage based on engineering (limiting factors related to degradation of physical systems, and consideration of repair and maintenance conditions) and economic (marginal cost-benefit analysis) criteria has clear limitations, as it does not consider the dynamic interplay of the factors affecting the actual durability, and the real value associated with the end of life options.

A key point emerging from this analysis is that durability, as a metric of the actual useful life, should be considered as a dynamic attribute, rather than static – defined at the design stage as an optimal design life target. While the engineers still need reference targets to evaluate their designs against, these targets need to include considerations of the end of life options; firstly, options for extending useful life of the product with ISHM, and secondly, the durability of components and modules should warrant higher value re-use and upcycle options, in addition to more costly re-manufacturing and recycling.

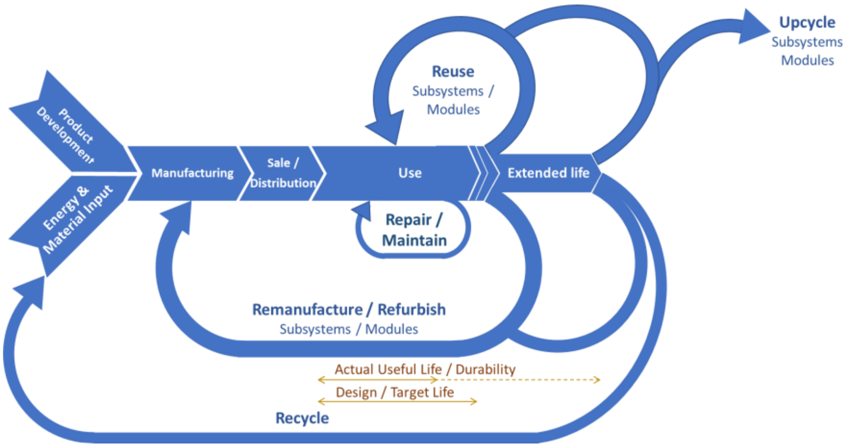

Figure 2. Durability view in the context of circular value chains

Another key point from this analysis relates to the variability seen in the actual durability, linked to the user behaviours (as illustrated in Figure 2). Achieving any circularity benefits from designing for extended lives significantly depends on the societal and individual preferences and attitudes to the extended life options: willingness to keep a product for longer, willingness to repair and mend products, willingness to re-use or use second-hand or second-life products. In the long term, engaging with users collaboratively around extending the life of products is going to be key. In short term, accounting for the dynamic impact of various factors affecting the actual durability (as stochastic modelling of actual durability) is essential for modelling value and costs at the design stage, as illustrated by Amatuni et al (2023) with stochastic modelling accounting for second hand use.

This paper also makes the argument that optimising durability through design for a circular economy requires a holistic consideration of techno-socio-economic context, factors and options, which is why much of the analysis has been presented in the form of trade-offs. This approach is in line with much of the recent research work, which draws attention that single-point focus on circularity options might have counterproductive effects (e.g. Figge et al (2023)).

The proposed goal-focussed definition of durability enables the necessary holistic consideration of the social, economic and technical factors, addresses the limitations of previous engineering-focussed definitions, and opens up new ways of considering and modelling durability within a circular economy.

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