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EcoMechatronics: Re-envisioning innovation for sustainability

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Abstract

*The chapter explores the concept of sustainability and its associated challenges within a mechatronics context. The primary aim is to promote critical thinking and innovation within an EcoMechatronics framing i.e. via an application of mechatronics that at its core works with Nature (rather than against it). Innovative technology per se is neither a force for good nor bad. However, EcoMechatronics permits a broader approach to innovation by considering socioenvironmental aspects as instrumental to improved performance, not as mere "*add ons*". Throughout the chapter, the authors tease out how innovation for sustainability can be so much more than merely doing "*less bad*" (e.g. fewer emissions or less waste) when we are capable of doing "*more good*", for example, by improving the soil or capturing and regenerating energy that would otherwise have dissipated. While the authors do compare two potential braking systems within an EcoMechatronics framing, their goal is not to provide a tick box methodology or a one size fits all answer but instead to provoke deeper questioning and reflection that enables mechatronics practitioners to sustainably innovate according to their own specific set of circumstances and challenges.*

Introduction

The 1987 WCED report [1], often referred to as The Brundtland Report, is a seminal investigation into the necessity for global action to ensure that resource use does not adversely affect the environment to the detriment of future generations. A key concept within the report is that of '*sustainability*'. Since its publication, various actors in a wide range of professional disciplines and industry sectors have attempted to shape sustainable development, in accordance with the norms, values and practices of their specialism or field. This chapter explores the concept of sustainability, innovation and their respective challenges within a mechatronics context. However, we do not just consider how mechatronics can be applied to environmental problems but rather highlight the added value of re-conceptualising mechatronics applications into an EcoMechatronics framing. The latter is an integration of knowledge and innovation across various engineering and computing fields in order to positively contribute to the environment. This means that EcoMechatronic design and practice goes beyond even a proactive anticipation of environmental harms and their mitigation because it leads those in the mechatronics field to design for an improved functioning of the ecosystem.

The notion of sustainability and how it leads to the expansion of mechatronics into EcoMechatronics is explored through an in-depth philosophical discussion on what is often considered to be "*green*", and why a much more nuanced positioned is needed if we are to truly innovate for sustainability. In particular, the authors consider (1) the extent to which relative efficiency gains are beneficial given that they are known to often trigger increases in absolute resource consumption; (2) whether the circular economy can exist given the physical limits of recoverability, as dictated by the Second Law of Thermodynamics; (3) whether recycling is sustainable and (4) the limitations of biomimicry and other "*green*" solutions. The purpose of this critical examination is not to criticise efforts thus far to achieve sustainable goals nor to suggest that none of these aforementioned practices have been beneficial. Rather it is to give mechatronics practitioners the questions they need to be able to ask to establish what is required of them if they are to direct innovation, and by extension society, towards a more sustainable path in the future.

What is sustainability?

The Brundtland Report [1] put forward the notion of sustainability as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." In this context, sustainability encompasses the following principles:

- The planet's ecology must be conserved, as the loss of plant and animal species is likely to impact upon the health and wellbeing of future human generations.
- Each generation has a moral obligation to conserve nature and maintain, and where possible improve, the planet's biochemical cycles.

These principles are rooted in a holistic understanding of planet Earth as a multifaceted and intricately interconnected complex system, whose health depends on the successful operation of all its parts and the relationships between them.

Innovative technology *per se* is neither a force for good nor bad. However, restricting what is seen as '*good*' to the optimisation of the socioeconomic system or to what is favoured by a select group of human individuals, as opposed to what is good for all of humanity and non-humanity, has often generated unforeseen system feedback mechanisms to the detriment of the whole.

An increasing awareness of environmental problems has led companies to embark on sustainability drives focused on reducing specific aspects of environmental harm. For example, in response to environmental damage, the aviation sector has set sustainability targets linked to reductions in CO_2 emissions. These targets can be achieved by reducing fuel consumption in absolute terms or by improving overall aviation fuel efficiency per air mile travelled, which is a reduction in fuel use in relative terms [2]. There is also a move towards new generations of aircraft using batteries, fuel cells or hydrogen [3, 4, 5] as alternatives to fossil fuels and commercial options for such aircraft are becoming increasingly viable. There are, for example, concepts for hydrogen-fuelled airliners being put forward by Airbus which combine hydrogen-burning gas turbines with hydrogen fuel cells that generate sufficient electrical storage capacity to carry up to 200 passengers for a predicted range of 2,000 nautical miles [6]. However, we are still some way from introducing these kinds of systems into commercial passenger operations. In the meantime, improving conventional fuel efficiency remains the principal strategy for sustainability.

Improved fuel efficiency offers considerable cost savings [7] and results in lower levels of air pollution per air mile travelled [8]. However, net environmental benefits will only occur if there is no increase in the number of air miles flown. In other words, any carbon emission reductions per air mile will only result in a better environment if cost savings *discourage* or *stabilise* air travel rather than promote additional travel. However, if a company can make more profit per mile flown through fuel savings, are fuel efficiency improvements likely to incentivise or reduce the market offer for flights? If cheaper fuel costs are passed onto the consumer because an airline wants to increase its market competitiveness, will this encourage the consumer to travel further or more often, as it is now cheaper to do so? This highlights the fact that even with the best intentions, it can be extremely difficult to argue that resource and/or carbon intensive industries can ever have green credentials or meaningful contribute to a transition towards a more sustainable economy.

The paradoxical relationship between fuel savings in relative terms and increased consumption in absolute terms was documented in the 19th century by Stanley Jevons [9]. Jevons identified how technological innovations such as the steam engine and better iron smelting methods, increased resource efficiency, which paradoxically increased resource consumption because cheaper commodity and energy prices heightened production demand [10, 11]. This paradox continues into the present day as shown in Fig. 1, which highlights how increases in UK fuel efficiency in cars has, at least in part, enabled a higher overall fuel consumption nationally. Such consumption patterns accelerate changes in travel preferences, and consequently in travel infrastructure, thus a societal preference for cars leads to more roads and less public transport, creating and maintaining unsustainable consumer lock-ins. Here, the term '*lock-in*' refers to the phenomenon that occurs when our present decisions tie both present and future generations into behavioural patterns that are not easy to eradicate. Negative lock-ins are then those that diminish the quality of the environment rather than improve it [12].

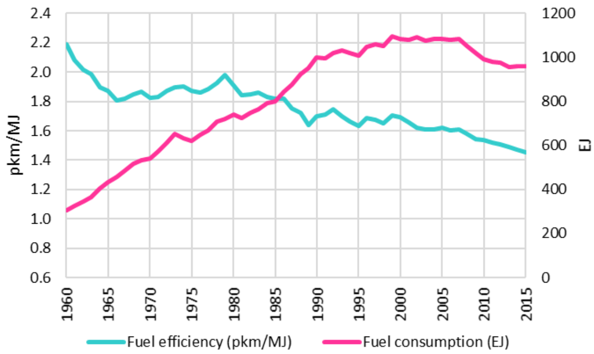

Figure 1. An example of the Jevon Paradox: UK car fuel efficiency vs total fuel consumption. Source: data {Rodrigues et al.} [13]

Understanding the attitudes and behaviours of businesses and society, as explained through the Jevons' Paradox and the concept of consumer lock-ins, is key if mechatronic designs are to work with nature and support sustainable development. The notion of a *Circular Economy*, whereby the quantity of resources used and waste/emissions created are reduced, is being promoted as one way of thinking sustainably. This is due to its emphasis on the ability to reuse, repair, refurbish, maintain, and recycle materials [14, 15, 16]. Extending material life expectancy through a cyclical approach that re-integrates waste material back into the socioeconomic system, rather than letting it leave via incineration or landfill, reduces the extraction and consumption of virgin materials and frees up land that would be otherwise designated to, or detrimentally affected, by waste management operations. The sustainability of the circular economy rests on the idea that humanity can self-contain its demand within a closed loop system because eventually there will be a peak in resource extraction, meaning that society will no longer consume more than what has already extracted.

The problem is that the Second Law of Thermodynamics dictates that with each cycle both the *quantity and quality* of resources degrades. In turn, this means that significantly, and successively more, energy and raw materials will be required to recover end-of-life material so that it is in a useable state. The Second Law also ensures that it is *physically impossible* to recover all material. No matter how careful one is or how efficient our technology, some material will inevitably leave the system. No amount of innovation can change this fact and the best we can hope to obtain is a spiral rather than a circular economy [17]. Physical limits aside, there are also socio-political obstacles hindering the development of cyclic/spiral consumption patterns. For instance, to what extent can a circular economy operate alongside political influence and interference, which encourages rather than constrains economic growth?

This does not mean that the circular economy holds no value [18]. Indeed, its sustainable outlook on a complex problem has moved society in the right direction. Amongst other things, its strategies have led to a reduction of some end-of-life issues because of its promotion of a more sustainable design stage. Appropriate designs can effectively remove various downstream problems before they occur [19, 20]. They can also begin to mitigate some of the unforeseen damages, such as the plastic fibrous releases from clothes, which contaminate the oceans [21, 22, 23].

Decisions at the early stages of a product's lifecycle also have the potential to either create or avoid trade-offs [24]. These include those linked to resource efficiency and product recyclability, reparability, and life expectancy. Policy development and legislation can also support circular economy initiatives. For example, through the "*right to repair*" and a ban on planned obsolescence, as enacted by the French Law *n°2020-105* [25], society can create a more sustainable path forward. This legislation grew out of consumer dissatisfaction with planned obsolescence and the concerted efforts of the French consumer group *Halte à l'Obsolescence Programmée*[1]. This built on the 2015 French Law *no. 2015-992* on *Energy Transition for Green Growt*h[2] [26], which made planned obsolescence an offence.

In 2018 the Italian Competition Authority, *Autorità Garante Della Concorrenza E Del Mercato*, fined two hi-tech companies for forcing users to accept software that slowed their devices, leaving them with little alternative but to buy newer '*faster*' devices when their older ones were, if not for the updates, fully functioning [27]. Laws and legal proceedings underpinned by circular economy principles certainly hold merit, but how effective are they against the many commercial pressures to manufacture new products? How will designers influence the re-education of society regarding the role of technological innovation and lifestyle choices? To what extent can *national* laws address the *global* socioenvironmental cost of throwing away items long before they have reached the end-of-life stage?

Another complex problem linked to product longevity is that replacing a boiler that is perfectly functional but not very energy efficient with a newer one that is highly energy efficient is only a sustainable solution to environmental harms *if* we restrict our scope to carbon emissions. However, if one focuses on the environmental harm caused by waste generation, then replacing the boiler is completely unsustainable. The notion of sustainability, in its truer sense, is a holistic one that requires a careful consideration of not only how nature operates but how it *flourishes*. The best strategies, including designs and ways of working, are those

[1] HOP - Stop Planned Obsolescence

[2] Energy Transition Law

that harmonise rather than antagonise biochemical cycles. They support rather than encroach upon plant and animal populations and their habits. This is the kind of innovation we propose in the transition towards a more sustainable approach to mechatronics design and function.

Nature, inspiration and learning

Nature operates efficiently because everything is useful and there is no material waste. Whilst the answer to '*what is nature*?' goes beyond the confines of this chapter, it is a system from which we have much to learn. Humans form part of this system and, as an integrated part of it, what we do impacts on the rest, sometimes for better and sometimes for worse. As part of the system, we are also reliant upon its offerings and subject to its feedback mechanisms, including those that we accidentally, or purposefully, influence or manipulate. Whilst a relatively straightforward notion to grasp, it appears that we humans often fail to recognise that we are very much a product of nature and that nature is affected by, and evolves alongside, us. In this respect, we can choose to contribute positively or negatively to the health of the whole. Given that we are all intricately linked and thrive, or fail, together, it makes sense that we work with, rather than against, nature.

Studying nature provides both a source for inspiration and a repository of knowledge, which we can use to improve the world around us [28]. Natural cycles always tend towards equilibrium, the lowest energy state possible, and they operate in closed material loops. In nature, the inter-dependencies among organisms operate on the basis that the needs of one organism are met in some form or another by the constant rejuvenation and re-packaging of resources that have previously been used by another. Some forward-thinking innovators have begun to re-envision resources in this way via what has become known as '*Cradle to Cradle*' thinking [29]. This concept challenges individuals and corporations to go beyond the mindset of '*doing less bad*'[3] and invites them to reframe the problem in terms of '*doing more good*'. Fundamentally, it leads to the setting of positive targets such as creating compostable cups that can provide nutrients and improve soil structure. These kinds of targets encourage designs and practices that seek to avoid waste altogether by reconceptualising it and using it to improve the functioning of the ecosystem. Once we begin to think and act in this way, it becomes difficult to accept waste as an inevitable necessary consequence of production. Instead, we begin to understand it for what it is in many instances, namely a *design* failure and a lack of imagination [30, 31]. This paradigm shift is built upon asking more challenging questions such as why settle for trying to reduce the amount of toxins we emit to the environment, if we can simply avoid them altogether? Why assume there is a trade-off between designing for aesthetics and sustainability? Why only substitute materials for

[3] For instance by producing less carbon emissions or solid waste.

cheaper options, if we can substitute them for better ones? Asking ourselves these kinds of questions opens up the possibility of re-purposing, re-integration and upcycling rather than merely thinking about how we might rescue resources from landfill via recycling [32].

The problem with recycling is that it results in material degradation and is not an effective method for preventing landfill in the long term. It also does little to increase resource utility. Even recycled steel and paper which are, arguably, two of the biggest success stories, have restricted uses because the virgin material is inevitably of better quality.

Taking the engineering example of a retaining wall, we can compare two different sustainable design proposals. In option 1, the approach may be to adopt concrete but reduce its environmental impact during the extraction, processing and production stages, by proactively reducing energy intensity and, consequently, CO_2 emissions, which are considerable [33, 34]. Yet producing cement as just one material for concrete, even with best available technology, is still energy intensive and emits various pollutants during processing [35, 36]. While improvements in cement manufacturing thus far have been significant [37], it still results in wastewater effluents, solid waste (e.g., cement kiln dust), particulate matter and considerable freshwater consumption [38]. Concrete is also difficult to recycle with each re-use resulting in material degradation and a reduction in consistency and strength. Some improvements have been made via microwave ovens. Certainly, the 0.93-2.86 kgCO2/t aggregate is considerably lower than the kerosene furnace/rubbing or rotatory kiln/sorting process that generates 69.53-98.01 kgCO2/t aggregate [39]. The microwave oven route also provides a higher quality recycled aggregate which increases potential uses and price [40]. This is certainly progress towards the closed loop process is made, but is there a better option?

In option 2, there is a vegetated retaining wall, which offers a structural design option that makes use of upcycled plastic that also supports plant and insect life, because it forms an extended part of their habitat. Vegetated retaining walls are not a new idea, and there are various examples going back more than 2,000 years, which made use of local and readily available materials such as reeds, willow and branches for reinforcement [41, 42]. All these materials are biodegradable and offer similar performance characteristics to newly developed innovative geosynthetic materials such as Flex MSE [43], which are much less biodegradable [44, 45].

Perhaps, an even better design option is to mimic nature rather than trying to become '*more sustainable*'? Biomimicry can give us models to work from which involve, for example, the observing of birds and their nest making activities, as a means to appreciate the physical limits of what is achievable in sustainable design and practice [46, 47, 48].

The Beijing National Stadium, designed by Swiss architects Herzog & de Meuron, is often described as the '*bird's nest*' stadium. This description comes from the appearance of the steel structure with interwoven twigs resembling an upturned nest [49]. The amount of steel required was approximately half of that under a typical stadium design and infill materials between the structural elements for insulation and protection from the elements decreased structural loading, via the of Ethylene tetrafluoroethylene (ETFE) panels [50]. The problem with ETFE lies with its recyclability in comparison to other potential options given that it is a plastic-based material. There were also some missed opportunities for doing more good when it comes to covering the stadium's needs, for instance solar energy covers only the stadium's underground parking requirements [51].

This raises the question of just how far can we realistically adopt biomimicry as a specific source of eco-design inspiration? Even as we learn from nature and align our behaviour and technology more closely with natural systems, there will inevitably be constraints and compromises at each step of the lifecycle, even if the goal is to design in such a way that the outcome contributes more to the environment than it takes out [52].

Sustainability Assessment and Life Cycle

To solve some of the issues mentioned above one can undertake sustainability assessments to objectively determine whether the solution proposed is better than other reasonable alternatives. One particularly useful tool is Life Cycle Assessment (LCA). According to Curran [53], the purpose of a LCA is to identify, qualify and quantify the environmental impacts generated within a given scope. An LCA thus permits the establishment and the quantification of the environmental impact inventory associated with a given product or service. It is used to state and compare environmental impacts from the cradle to the grave, meaning from extraction to disposal [54]. For an LCA assessment, one calculates that which enters the system (in terms of raw materials and energy) and that which leaves (i.e. air, water and residual solid emissions). These flows are then summed and subsequently represent the total effect of that product or service on the environment. All informational inputs should be transparent and objective. That said, an LCA is not a completely objective method and typically involves some form of interpretation. The scoping exercise and the defining of boundaries is also subjective, albeit based on objective factors. Any assumptions or purposeful exclusion from a case study should be stated as such [55]. For example, does the scope range from gate-to-gate (solely production processes), well to wheel (fossil fuel extraction to mechanical drive) or cradle to grave?

A well-considered LCA will enable a company or individual to calculate the sustainability of a product at each step across multiple environmental aspects such as material recovery, energy efficiency, carbon emissions and waste generation. To use an example, one can consider whether the upcycling of an end-of-life machining knife to a new wood turning tool is sustainable beyond the mere fact of delaying disposal and removing the need to mine for the metal associated with the wood turning tool. To do this, one could calculate the carbon footprint of the upcycled tool with an identical one made via conventional production. It may well be that the carbon emissions released during the grinding of the machining knife to provide the metal for the wood cutting tool is just as high, if not higher than the production of metal extracted from an ore and manufactured into a metal sheet. Of course, carbon emissions are just one aspect, which is why the weighting of all impacts is important. If one wishes to prioritise metal recoverability, then the LCA will indicate a positive result because the metal is upcycled rather than downcycled scrap. If one considers energy to be of primary importance, it may be that the upcycling has a negative result. Hence the subjectivity of an LCA. It may also be that the environmental considerations are secondary to social issues such as mining encroachment on indigenous land or child labour in mines. In such a situation, the above LCA would need to be expanded to into a Life Cycle Sustainability Assessment (LCSA), which incorporates life cycle costing (LCC) and social life cycle assessment (sLCA). LCC takes into account the economic costs of the raw materials, equipment, energy, and labour costs associated with product processing. A sLCA evaluates worker safety, delocalisation and migration, child labour practices, corruption issues and respect of indigenous rights [56]. One way to reduce the probability of these issues is through tracing and reducing the complexity of the supply chain. The LCA/LCSA helps with this objective because it encourages both transparency and accountability.

EcoMechatronics

Before exploring the nature of EcoMechatronics and how we can use it re-envision innovation, a brief analysis of Mechatronics and its purpose is required. Mechatronics is an interdisciplinary engineering subject that integrates aspects of mechanical engineering, industrial engineering, production engineering, civil engineering electronics and computer systems with advanced controls for the designing, construction, and operation of '*intelligent*' (but not necessarily smart) products and processes [57]. The term smart has come to mean, in practice, the capability of being interconnected via the internet, including situations where there is no embedded capacity for data interpretation or analysis; thus '*smart*' tends to imply connectivity as part of the Internet of Things (IoT) and is a misnomer in that it does not actually mean that in every case there is an embedded capacity to make decisions on received data.

One area where mechatronics is extremely prevalent is in the transport sector. In 2010, 30 to 35 percent of a new, higher class, passenger car's economic value was linked to the embedded electronics and mechatronics. This is unsurprising given that such a car will typically contain 2.5 km of cables, approximately 40 sensors, 100 to 150 electromotors, and 45 to 75 microcontrollers of various types [58]. Mechatronic elements have also been increasingly incorporated into vehicles in response to environmental regulations, particularly in respect of emissions and air quality standards [59]. There has also been an increasing awareness that engineers must consider performance factors relating to customer satisfaction and economic cost reduction strategies [60].

Mechatronics, as a discipline, is also significant when one considers the potential for Autonomous Vehicles to influence not just the economy but how we think about road travel. An early mechatronics system introduced into vehicles was the anti-lock brake system (ABS) in the 1970's, enabled through developments in integrated electronics and microcomputers [61]. Since then, there have been various developments including traction control systems and, more recently, adaptive cruise control and automatic motor stop systems. The latter saves on fuel consumption by shutting the engine down when the car is operating but at a standstill.

Mechatronic elements are also favoured relative to conventional options as they tend to be lighter than the mechanical components they replace, leading to a lower fuel consumption and a lower power level needed to obtain the same level of technical performance. However, as we have made clear in the previous sections, using mechatronics to reduce vehicle weight or within cost cutting options does *not* automatically, or necessarily, lead to a sustainable policy or practice. This is especially the case if mechatronics solutions result in downcycling and an increased tendency towards landfill disposal, instead of recuperation, re-use, recycling and upcycling. In fact, and as we have already suggested, shifts towards mechatronics solutions that solely focus on energy savings at the cost of material efficiency or which fail to consider a more holistic evaluation of system efficiency can exacerbate rather than mitigate environmental issues.

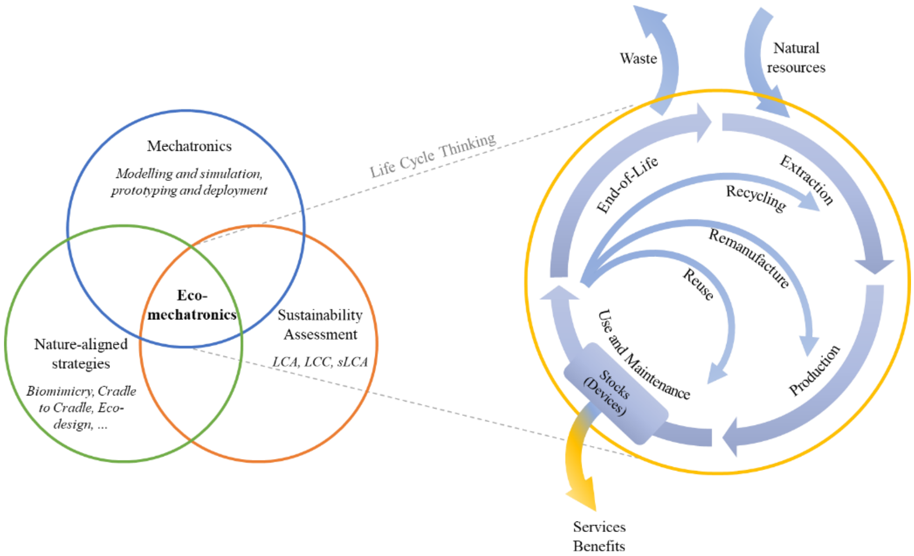

Figure 2. A conceptual model for the EcoMechatronics approach.

This is where an ecomechatronic approach comes in, whereby the utility of mechatronics is not just concerned with higher system performance in and of itself, or merely in relation to economic factors, but in terms of how the system and its parts impact upon the environment. Consequently, our conceptual framing of EcoMechatronics is as an interdisciplinary engineering subject that integrates knowledge and innovation across various engineering and computing fields, including environmental engineering and earth system science to ensure that the design, construction, and operation of '*intelligent*' products and processes positively contribute to the environment and all those living beings that rely on optimally functioning natural processes (see Fig. 2).

Braking system – an EcoMechatronic case study

We will here examine an EcoMechatronics approach via two braking systems. The design of braking systems has typically been in terms of system performance linked to the benefits accrued in reducing vehicle weight and vibrations while improving braking effectiveness, system safety and reliability at a lower cost [62]. The environmental impact of the system's materials is not a conventional performance characteristic and are therefore typically ignored or of secondary importance. An EcoMechatronics approach means that the sustainability of the materials used in braking systems becomes a core criterion, rather than an added bonus. Moubarak et al., [63] provide an excellent EcoMechatronics example via their redesign of a brake system, which couples a magnetic brake to a regular brake. Their aim was to reduce the friction that causes copper to detach from the brake pad following its wear and tear.

Elevated copper levels are toxic to aquatic life, causing mortality, morbidity and detrimentally affecting fish reproduction and growth. According to the US Environmental Protection Agency [64], brake pads are a significant source of the problem. This is because they are responsible for 24g to 192g of copper being released into the environment, following road surface runoff, over the lifetime of the average car [63]. This problem is compounded by the fact that car ownership and use is increasingly prevalent. The global car fleet, for example, expanded from about 51 million in 1950 to over 800 million in 2007 [65]. The prototype developed by Moubarak et al. [63] reduced copper release by up to a third. The reduced friction also increased the brake longevity and consequently reduced waste disposal. However, the design by Moubarak et al. is still an example of doing '*less bad*' rather than '*more good*', in the sense it merely reduces copper contamination rather than innovates for positive environmental impacts.

In comparison, and as an example of a braking example that attempts to '*do good*', we can examine regenerative braking systems (RBS). The principle behind this system is straightforward. In the process of reducing vehicle speed, the RBS transforms kinetic energy into electrical energy, storing the electrical energy recovered in accumulators or batteries for later use [66]. This reduces the need for further inputs as some of the energy that would have dissipated is captured. It also reduces emissions either directly, through the reduced combustion of vehicle fuel, or indirectly due to the lower quantities of fuel consumed during the electricity generation process.

In one road test study, the incorporation of RBS, significantly reduced CO_2 exhaust emissions from hybrid vehicles. CO_2 reduced from 140 g/km of CO2 to 108.4 g/km of CO_2 or from 44.8 g/km to 67 g/km, depending on the driving mode [67]. There are other positive benefits. Laboratory tests show up to a 10 to 30 percent decrease in electrical energy consumption from the electric/hybrid vehicle battery when RBS is utilised [68, 69]. RBS has also been shown to reduce braking friction, which as explained above reduces environmental contamination [70] in additional to noise, while increasing the longevity of the component parts [69]. This is exactly the kind of innovative design and operation that those who wish to work in EcoMechatronics need to envision when designing for a sustainable future, precisely because it does not stop at merely doing '*less bad*'.

Conclusions

The chapter explored the concept of sustainability and its associated challenges within a mechatronics context. The primary aim was to promote critical thinking and innovation within an EcoMechatronics framing, namely an application of mechatronics that at its core works with nature rather than against it, to foster a better environment.

The conceptual framing of EcoMechatronics is as an interdisciplinary engineering subject that integrates knowledge and innovation across various engineering and computing fields in order to positively contribute to the environment. Innovative technology *per se* is neither a force for good nor bad. However, given that we are all intricately linked and thrive, or fail, together, it makes sense that we work with rather than against nature and use it as a source for inspiration, and a repository of knowledge, to improve the world around us. In nature, everything is useful and there is no material waste. Some forward-thinking innovators have begun to re-envision resources in this way via what has become known as *Cradle to Cradle* thinking. This concept challenges individuals and corporations to go beyond the mindset of '*doing less bad*', as for instance by producing less carbon emissions or solid waste and invites them to reframe the problem in terms of "*doing more good*". This reframing encourages designs and practices that not only avoid waste altogether but actively use the '*waste*' that cannot be avoided to improve ecosystem function.

EcoMechatronics offers the conceptual framing needed to ask questions that will lead engineers and corporate leaders to align their targets and measure product performance against multiple socioenvironmental considerations with the end goal being sustainable development. Key questions might include:

- How do we as a company engineer our products so that we do more good, rather than less bad?
- What would such policies and designs look like in practice?
- What data do we need to collect and metrics do we need to invoke to ensure that our product (or service) contributes to the environment rather than merely mitigates our impacts?
- How does one go beyond environmental rhetoric and execute actionable plans with clear milestones?
- To what extent can we upcycle rather than recycle or avoid landfill?

And finally, how and to what extent can mechatronics solutions advance sustainable innovation and support critical thinking for the benefit of both present and future generations?

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