Chapter 2
Consumption to Contribution: Sustainable Technological Development Through Innovation

John H. Millbank[1]

2.1 Introduction

Sustainability issues have been driven to the top of the political, economic and societal agenda, particularly in regard to unremitting consumption of finite resources and its impact on environmental degradation.

In her landmark, but at the time (1962) controversial book, *Silent Spring* [1], Rachel Carson drew to the world's attention the impact of pesticide use on wildlife, opening the debate on environmental degradation. This was followed a decade later by *The Limits to Growth* [4], an equally controversial study on behalf of the Club of Rome.[2]

However, it was not until the Brundtland Report appeared in 1987[3] that issues of sustainable development began to be taken seriously. These issues were taken up by the business world with respect to:

> How the business community can adapt and contribute to the crucial goal of sustainable development which combines the objectives of environmental protection and economic growth.

This occurred under the auspices of the Business Charter for Sustainable Development in the publication *Changing Course* [5].

The aim of the present chapter is to provide an introduction to 'applied' sustainable approaches to technological development through innovation designed to secure 'triple bottom line' outcomes[4].

---

[1] Technology Transfer Consultant, UK

[2] Other notable commentary from around that period was by Commoner in *The Closing Circle* [2], and Dubos and Ward in *Only One Earth* [3].

[3] See Chapter 1

[4] The triple bottom line is defined as: society depends on the economy and the economy depends on the global ecosystem, whose health represents the bottom line [6].

2.2 The Interpretation of Meaning for Sustainability and Innovation

The terms innovation and sustainability have become widely appropriated in academic literature as well as by the popular press to convey an imperative related to future economic, social and environmental wellbeing. Moreover, these terms are very often juxtaposed to imply change from the *status quo* to more conducive conditions. Unfortunately, in this context they are amorphous and consequently their definitions have come to mean different things to different people. For example, the business community may regard innovation as a means by which to secure longer term sustainable commercial advantage and leverage whereas societal interpretations will, in general, be wholly concerned with affecting change leading to stability and global longevity. Understandably, therefore, there is a need to adopt an interpretation for both sustainability and innovation which in the case-based approach of the present book meets the needs of science, technology and engineering practitioners as applied to mechatronic system development.

The (UK) Department of Trade and Industry[5] offered a simplistic and rather anodyne definition of innovation as [7]:

> The *successful* exploitation of new ideas, products, materials, techniques and processes.

In contrast, the Brundtland definition[6] of sustainability is more emphatic. However, for the purpose of this discussion, both definitions remain inconclusive. Therefore, an attempt to follow the more rigorous interpretations offered by the Council for Science and Technology [8] for innovation, and Charter for sustainable innovation [9] provides the basis for delineating the consumption to contribution debate.

Innovation is the process by which ideas and knowledge are exploited for business purposes. It encompasses not only the creation of a new product, process or service, but also the systems, processes, organisations, structures and all other aspects of a company's existing or future competitive edge such as distribution, marketing, branding and indeed the creation of a brand new market. The process draws on a range of intellectual and other inputs including knowledge of markets, customers, competitors, science, engineering and technology (CST).

Sustainable Innovation is a process where sustainability considerations (environmental, social, and financial) are integrated into company systems from idea generation through to research and development (R&D) and commercialisation. This applies to products, services and technologies as well as new business and organisational models [9].

---

[5] Now remodelled as the Department for Business, Enterprise & Regulatory Reform, whose innovation home page defines the process as '*the successful exploitation of new ideas*'; a further dilution of meaning. The original DTI online document has been deleted; the archive of which is reported to be with the British Library.

[6] Chapter 1 Op. cit.

Thus, a context is established from which to explore the contribution that mechatronic engineering and technology practitioners can provide towards reducing consumption of finite resources, selecting appropriate technologies, ensuring minimum energy usage, eliminating unnecessary waste, extending reliability and endurance, avoiding undesirable duplication, future proofing, end-of-life recovery of component stocks, reducing/negating pollution and toxicity and simplifying functionality through the rationalisation of complexity. Mechatronics is a synergistic discipline which seeks to secure integrated solutions. Under these conditions, a more holistic approach to creating 'sustainable' products, processes and systems can result, and thereby engage a perception that:

> The whole is more than the sum of the parts – and each part is more than a fraction of the whole [10].

For mechatronic applications, there are several instances where this philosophy may be seen to already be making an impact including:

- combining electroencephalography (EEG) with magnetic resonance imaging (MRI) [11];
- control software integration [12] for investigations into epilepsy [13];
- the Combined Active and Passive Safety System (CAPS) for automotive applications under development by Bosch and others [14, 15];
- micro-electromechanical systems (MEMS) arrays offering the possibility of thousands of individual components to function in isolation or combined to enable complex actions [16–18].

2.3 Deconstructing Technological Innovation as a Driving Force for Sustainable Engineered Systems

Innovation, as such, is regarded as both a cause and solution to much of the structural, environmental and social impact issues surrounding economic development [19]. Yet, it is argued that technological innovation lies at the heart of attempts to secure sustainable 'engineered' system outcomes for longer term social and economic gain and in turn should be appropriated to advance environmental sustainability. This contrasts with systems innovation where broader concerns are primarily directed towards organisational, architectural, socio-political, and socio-technical issues within the sustainability framework [20].

In recent years, linear models of innovation[7] have been largely discredited [22] as inadequate descriptors for differentiating the various and often complex processes in translating concepts to a marketable conclusion. While the

[7] As a sequential and unidirectional process having five functional phases comprising: idea generation > invention > R&D > application > diffusion [21]

interactive, systems-based model offered by Rothwell [23] does overcome many of the shortcomings of its predecessors, it still fails to take account of the need to incorporate environmental impact and sustainability considerations, or indeed the influence of moral imperatives [24][8]. This is further aggravated by the requirement, for instance, to absorb within the process energy demands [26] and water consumption [27] both during system configuration and lifetime usage (and possibly disposal). As Rosenburg [28] points out with respect to energy consumption:

> Nor is it sufficient to examine only the energy efficiency involved in the manufacture of a product; equally important are the energy-using requirements of the product over the course of its own life cycle.

One of the early attempts to address environmental concerns and sustainability within an entrepreneurial framework of technological innovation was characterised in the work of Martin [29, 30], which provided an outline of 'technological assessment processes and environmental impact statements'.

As Herkert *et al.* [31] observed:

> One of the crucial elements of sustainable development lies in understanding the role that technological innovation plays in the process. Because technology often drives the way in which humans consume resources, create waste, and structure society, its role is significant.

By implication, the transition of a discrete technological innovation to the applications, exploitation and diffusion arena[9] is probably the most important issue for the design engineer as far as sustainable outcomes are concerned. It engages a set of processes where life cycle assessments, materials utilisation, energy efficiencies, and other imports should be addressed both upstream and downstream[10] of the 'technological transfer' domain [37].

Rogers and Valente [38] have described technology transfer as:

> The process by which technological innovations are exchanged between individuals and organisations who are involved in R&D (but not exclusively) on the one hand, and putting technological innovations into use on the other hand…..Traditionally, it was conceptualised as the transfer of hardware objects, but now often involves information.

Unfortunately, this description omits any reference to fitness-for-purpose, economic configuration, societal acceptance, or indeed environmental and ecological impact factors. Moreover, demonstration of technology in one area of application may not necessarily hold up in another. Thus, the design engineer is faced with the problem of attempting to secure robust functional solutions within

---

[8] Ethical determinants with respect to mechatronic product development have been explored by Searing and Rabins [25].

[9] There are several sources of information on taking ideas to exploitation available. Readers are particularly encouraged to consult [32–36].

[10] Incorporating forecasting, foresight and technological verification assessments

ever more restrictive regimes of outcome conformity, moral conduct, and sustainability promotion.

2.4 Forecasting, Foresight and Technology Assessment

Although often regarded as one and the same, there are unique distinctions between forecasting and foresight [39]. The techniques and visualisation tools they employ have special significance for sustainability criteria in technological exploitation for economic, societal and environmental benefit. Both processes are important adjuncts in the technological innovation paradigm [40], and bring urgency to the issues of future consumption, technological progress and environmental tensions surrounding the sustainability debate.

Foresight studies have been advanced over the last twenty years [41], whereas forecasting and technology assessments have been part of the strategic armoury of industrial organisations and government agencies for considerably longer, invoking techniques such as the Delphi methodology, morphological analysis and relevance trees [42, 43]. Nowadays, forecasting might be more closely aligned with that of 'applications' foresight to assess, for example, the impact of a well-defined and potentially transferable technology into applications which might not otherwise have been envisaged or intended, such as laser interventions in surgery. Consequently, whereas forecasting is an engagement that attempts to predict future impacts and outcomes precisely, foresight:

> *Explores* possible future directions of technological progress and identifies forces that might drive certain developments, and thus provides decision-makers in politics and companies with such types of strategic information [44].

This contrasts to some extent with technology assessments which Coates [45] defines as:

> The exploration of primary and secondary consequences of the introduction into society of a new technology or the expansion of an already existing technology.

For the mechatronics system developer and practitioner, the technology assessment approach arguably offers the most appropriate and accessible mechanism in which to incorporate life cycle and environmental impact analysis, for example, into design studies [46] for the promotion of sustainable outcomes. This can be summarised as an exercise of gathering sufficient information about the technological development in terms of resource appropriation, processing, energy premium, anticipated durability, etc. and:

> It's likely future consequences for all those who interact with it, *before* embarking upon developing or deploying this technology [47].

Van den Ende *et al.* [48] offer a classification of the approaches and methods of technology assessment for unification into a common framework, whilst other contributions which have particular significance for mechatronic systems developers and problem solvers are provided by Gausemeier [49], Fey and Rivin [50],[11] and Kuntze [51][12].

Foresight evaluations, by contrast, remain more speculative when attempting to secure practical and robust technical solutions and, in general, remain within the domain of policy and executive decision makers. However, the context with which mechatronics is perceived as a synergistic and unified multi-dimensional discipline embraces the wider imports of social, political, economic and environmental issues.

Nowadays, delineation of foresight perspectives has evolved into a third generation, the first having been ‘driven by the internal dynamics of technology’, the second embracing ‘technology and markets’, and the third being ‘enhanced by the inclusion of the social dimension’ [53]. Within this paradigm, the critical issue of sustainability becomes all too apparent. Borup [54] deals with these concerns within a framework of principles, which addresses:

> Production/consumption systems, eco-efficiency, risks & uncertainty, institutional reflexivity, values and visions.

2.5 The Influence and Impact of Information and Communication Technologies

Developments in computer and telecommunications technology have transformed virtually every aspect of economic and social activity in the ‘developed’ world, and increasingly so within developing nations. Whilst it is not possible to deconstruct the pervasiveness, and some would argue invasiveness, of the constituent technologies, there is much to debate in terms of sustainability issues relating to both functional implementation and, more particularly, to environmental impact.

In 1978, Sloman [55] declared that:

> It can be argued that computers, or to be more precise, combinations of computers and programs, constitute profoundly important new toys which can give us a new means of expression and communication and help us create an ever-increasing new stock of concepts and metaphors for thinking about all sorts of complex systems, including ourselves.

For the mechatronics practitioner or for that matter anyone else who routinely uses computer-aided, internet-enabled, microprocessor-derived technologies, the consumption to contribution imperative becomes difficult to reconcile and negotiate. A few application-specific examples illustrate just how challenging it is

---

[11] Incorporation of the Theory of Inventive Problem Solving (TRIZ) within forecasting to remove ‘trial and error’ ambiguities

[12] Detailed evaluation and comparison with earlier studies has been carried out by Cuhls *et al.* [52].

to ensure sustainable outcomes which affect net gain for society, the economy and, ultimately, environmental wellbeing.

For instance, email and internet-derived resources *should* have led to the 'paperless office' through digital storage and archiving [56]. In fact, evidence strongly suggests otherwise, particularly in the exponential growth in paper consumption for email archiving [57]. Moreover, the provision of internet resources through the World Wide Web and its access to specific topics is only sustainable as long as it remains available and viewable (see footnote 4)[13]. This presents something of a dichotomy in the consumption to contribution debate. However, information flows through email and resources accessed through the World Wide Web do have many advantages as a medium for distributing tacit knowledge, although, whilst information management is well established, the management of knowledge remains in its infancy [58].

There is a notable difference between actively seeking out information and the passive receipt of it. As has been pointed out [59], the Web requires people to actively seek out the information, usually through search engines, whereas email and web blog discussion provides and promotes delivery of information without effort, thus providing an interactive mechanism of knowledge exchange. Furthermore, as a means to document knowledge, internet technologies makes an impact on virtually all aspects of technological development and organisational performance, ranging from scientific enquiry to sustained business and societal administration. Hence, the concept of knowledge and its transference through electronic means reveals distinct attributes as well as limitations.

This is explored by Davenport and Prusak [60], who assert that spontaneous, unstructured knowledge transfer is vital to a firm's success, and that they should shift their attention from 'documents to discussion'. They go on to describe the 'velocity' and 'viscosity' of knowledge transfer; velocity being the speed at which knowledge moves through an organisation and viscosity referring to the richness (or quality) of the knowledge transferred, and that these components are often at odds with each other. This can result in information overload and in the context of email, which was originally designed as a communications application, is often used for task management and personal archiving for which it was never intended [61].

The knowledge-based economy, through the implementation of information and communication technologies, has been described routinely as 'weightless' [62] since it was supposed to reduce dependence upon physical stocks of natural resources. However, this argument has been challenged in a societal as well as industrial economic context [63] and, more critically, within a sustainability setting [64] due to rebound effects of consumption. These are created by the proliferation of computer hardware, its obsolescence and redundancy, energy

[13] For this reason, hyperlink referencing within this chapter is, in general, confined only to documentation which would otherwise not be available through published 'sustainable' (*sic*) paper format. Another shortcoming is that, even with full html, pdf, etc. citing, direct access may be limited by filtering or by subscription registration by the user.

requirements for both powering and cooling an ever increasing demand for processing capacity as well as an expanding array of short life span consumer devices. Munn *et al.* [65] have examined the environmental and social implications of these issues and draw attention to the fact that in 1999, the average lifespan for a computer in the USA was between four and six years, whereas by 2005, it had dropped to less than two years [14].

Energy consumption also features as a primary concern not only in the power requirements to run massive data servers, but also in the need for cooling such installations [67]. Energy aware thermal management approaches [68] that deal holistically with the path of heat flux from the chip, through the system enclosure and out to the environment provide a mechanism for taking energy consumption issues seriously.

2.6 Consumption, Obsolescence and Moves Towards Future Proofing

Consumption and growth have been synonymous since the beginning of the first industrial revolution and, indeed, some economists would argue that it remains nothing less than the purpose of the economy [69]. Now in the 'information age', the world is faced with tensions of unprecedented demand for 'material' consumption to support technological progress together with ever increasing energy requirements, with which to stimulate consumer demand as well as to encourage take-up of newer technological artefacts and processes as they emerge. Inevitably, attendant resource depletion, waste generation and disposability problems have become *the* major contemporary sustainability issue [70] although, from a historical perspective, dealing with waste together with the concepts of Reduce – Recycle and Reuse over the past century [71] can be traced back thousands of years [72].

The impacts of the (current) IT revolution and its technological antecedents and derivatives were anticipated three decades ago when the notion of 'responsible consumption' [73] was first proposed. However, it is also now widely recognised that a transition to sustainable consumption demands greater urgency to ensure that quality of life and lifestyle can be maintained and enhanced [74, 75]. This is a subtle distinction since, whilst responsible consumption reflects rational and efficient use of resources, sustainable consumption invokes net societal and environmental gain. In order to support such objectives, it is essential to encourage more radical innovative approaches in the use and application of materials,

[14] The Deploy project (funded through the European Commission) aims to provide formalised engineering methods to secure dependable and more robust hardware across a range of industrial sectors, including transportation, automotive, space (satellites), telecommunication (mobile phones) and business information (computers), in particular dealing with pervasiveness and complexity [66].

technology and energy inputs. Therefore, an embedded business model and societal culture should be encouraged which seeks to eliminate unnecessary waste altogether, invoke only wholly renewable energy contributions[15] and rationalise essential natural resource extraction to avoid depletion. This is an ideal which may only occur through a revolutionary approach and outcome.

Reducing obsolescence and redundancy is a primary area to address since disposability has been the hallmark of the business world as well as that of consumers for too long. Its perceived survival and continued growth has been dependent on encouraging continued patterns of consumption [78] through limited life-cycle functionality (intended or otherwise), or the adoption of newer technologies as they become viable. Moreover, the acceleration of obsolescence, particularly in ICT, results in a loss of valuable knowledge as well as creating social disruption [79]. By contrast, customised low volume capital intensive products and processes (such as can be found in ships, aircraft, industrial plants and other large scale equipment) have problems with reconciling obsolescence, since they remain in service for many decades [80]. This, in itself, necessitates a step-change innovation in organisational response to secure product life longevity, to eliminate redundancy and, ultimately, demonstrate sustainable business practices. Understanding the factors which determine product obsolescence is an important consideration [81] and integrating obsolescence forecasting into the product design process can secure more sustainable outcomes [82].

Future proofing[16] is the generic form of 'obsolescence forecasting' and as such is a relatively new concept. It has evolved mainly through the business world to anticipate organisational needs and responses to changing business environments [83]. However, application specific areas – such as ICT industries seeking to ensure future compatibility of software for extended applications or system integration – indicate that the concept can be applied to more basic technological development areas such as sustainable automotive mobility [84]. Naturally, this offers an opportunity for the design practitioner to engage and integrate many of issues posed by earlier arguments surrounding environmental impacts and consequences of consumption and waste, by invoking foresight exercises [85] into decision processes as well as other approaches such as technology roadmapping [86, 87][17].

Unfortunately, demand only aggravates the consumption problem and the economy response to stimulate that demand through promotion of more than is actually wanted or necessary [88] by the business community in order to secure

---

[15] An example of efforts to address these issues [76] together with a wider ranging brief to promote Technologies for Sustainable Development may be found within an initiative set up in 2001 by the Austrian Federal Ministry of Transport, Innovation and Technology [77].

[16] Describes the ambiguous process of attempting to anticipate future developments, such as to avoid obsolescence

[17] Roadmapping is a requirements-derived technology planning process which assists in the identification, selection and development of technology alternatives to satisfy a set of product outcomes, and is particularly suitable for evaluation against environmental impact and sustainability criteria.

profit ‘bottom line’ objectives (See footnote 3). These are complex economic and sociological issues involving both product and process innovation, detailed examination of which remains beyond the scope of this chapter.

2.7 Complexity Paradigms Within a Sustainability Context

Technological innovation is increasingly concerned with complex products and processes [89], and even components and subsystems such as microprocessors or aircraft jet engines have evolved into highly complex technologies in their own right [90]. A failure in subsystems and components within a fully integrated mechatronic system will inevitably result in malfunction or inoperability of the whole product, process or equipment. Of course, a subsystem or component may not have failed, but just need replacement as part of an upgrading or improvement in functionality. In highly customised, capital intensive products (such as aircraft), many organisations and resources will be mobilised [91] to resolve the subsystem failure or upgrade. Moreover, a range of core capabilities will be retained and enhanced to deal with subsystem improvements and further system integration as they are developed over time [92].

By contrast, in mass produced commodity systems such as personal computers, for economic reasons, there may be no incentive or even possibility to attempt repair due to the complex nature of the failed component. This applies equally to a working system which may be perceived as having become functionally inadequate as a result of greater demands being placed on its processing capacity. This poses a moral dilemma [93], particularly in abandonment and disposal of the failed or working component (microprocessor) or, indeed, the whole system.

Adoption of concurrent engineering methodologies for complex systems may to some extent offer benefits of sustaining balanced stakeholder satisfaction over time [94], together with the adoption of platform-based development of product families [95] to improve longevity. Moreover, there are indications that efforts are being made to reduce the increasing energy premiums associated with the massive growth in processing capacity for ICT applications particularly within data server domains. For example, voltage and frequency scaling for computer hardware and HVAC[18] cooling infrastructure lowers energy consumption by reducing microprocessor performance during periods of low utilisation [96]. New generations of multi-core processors are being marketed for improved multi-tasking performance which also offer substantially reduced power consumption [97]. Of course, this all tends to add to the complexity paradigm, although even here, there are indications that attempts are being made to reduce complexity both in product design [98] as well as across the software-driven user interface [99]. However, obsolescence, redundancy and deficiency cannot be eliminated

[18] Heating, ventilation and air conditioning

completely. Consequently, the burden of consumption and its associated waste generation as well as the need for process handling remain inconclusive.

2.8 Rationalising Material Selection and Processing

Material consumption, along with its raw resource extraction and industrial processing, underlies and influences all technology-based outcomes whether they manifest themselves as consumer products or major capital intensive structures. Rationalising material selection to meet environmental objectives is, therefore, of greatest concern in product life cycles in terms of production, manufacture, use and disposal [100].

Manufacturers are beginning to adopt more sustainable material selection practices with the automotive sector, for instance, engaged in utilising more recycled materials into vehicles [101] as well rationalising design approaches to recycle-ability through its use of software tools such as *euroMat* [102]. However, of particular environmental concern is the widespread use of hydrocarbon derived plastic materials and the extent to which they lend themselves to recycling, reuse or, in the worst scenario, abandonment in landfills.

As an engineering material, plastics are the fastest growing group of bulk materials used in high income economies and have overtaken aluminium and glass in terms of mass quantities used [103]. Unfortunately, in sustainability terms, attempting to substitute plastic materials used, for example, in packaging applications with materials such as paper, glass or aluminium may be perceived as more eco-friendly, but adds to the overall weight, volume, cost and energy consumption [104]. Thus, the ubiquitous plastic-injection moulding together with more basic sheet and film variants form major structural components of virtually all consumer-oriented and industrial/commercial use products nowadays. Moreover, due to its versatility, form and function complexity, cheapness, reproducibility, range of engineering properties and mass-produceability, it enables structural configurations that would not be possible to create by any other 'one-shot' application. As such, plastic injection mouldings have become ever more sophisticated in their applications over the past 60 years. Therefore, the method of bulk material processing or recycling [105] together with injection moulding techniques (hydraulic, hybrid, all-electric) also becomes significant, particularly in terms of energy consumption [106].

Although conventional plastics are derived from finite hydrocarbon sources, they do lend themselves to energy recovery potential at the end of product life in certain instances [107], particularly where they cannot be recycled or reused. However, a more rational approach for the system designer is to adopt a cradle-tograve analysis to material flows [108], whereby energy and waste are considered at each stage of development and processing[19].

Biodegradable polymers [112, 113], by contrast, afford an alternative to 'conventional' plastics altogether, whereby environmental impacts are virtually eliminated through natural decomposition over a given timeframe. However, some early attempts within the European community to encourage industry to promote and prescribe the use of bio-plastics were not successful due to 'structural tensions' [114][20]; a particular example being starch-based plastic coatings of electrical wiring which, in service, suffered premature decomposition. However, much progress is being made in improving structural performance in the case of electric wiring [116] and in consumer products in general, particularly injection-moulded electrical goods such as DVD players, computer casings, etc. [117][21].

A major health issue associated with using, for example, conventional (PVC) polymers is that the vinyl chloride monomer is a known carcinogen. Additionally, in wiring applications, for instance, the inclusion of lead compounds (which produces good heat stabilisation characteristics) is considered both a health and environmental hazard [120]. Unfortunately, lead (together with several other widely used heavy metals commonly found in products and processes) require special considerations for disposal, due to toxicity. Consequently, elimination of lead and other heavy metals altogether from routine use is seen as an imperative[22] and, as such, forms a central plank of recent EU legislation. Under its directive on the restriction of the use of certain hazardous substances [122], it calls for substitution of various heavy metals and, more particularly, on waste electrical and electronic equipment (WEEE) which addresses the fast increasing waste stream of electrical and electronic equipment [123]. Nonetheless, there are instances where good intentions associated with the elimination of heavy metal compounds have resulted in unintended outcomes. For example, the requirement to use only lead-free solder in electrical circuit applications [124] can result in a phenomenon known as 'tin whiskers' [125, 126]. Over time, the condition sometimes results in catastrophic short circuits in electronic components, rendering complete system failures and possible abandonment; hardly a move towards sustainability.

Thus, rationalising material selection and processing necessitates a holistic approach to integrating sustainability, as typified within the MATISSE project [127]. As Ritthof [128] points out:

---

[19] More general reference to plastics and polymeric product life cycle assessment within the context of environmental impact and sustainable outcomes can be found in [109–111].

[20] Further explanation on the origins and interpretation of the term 'structural tension' within an innovation context is given by Carlsson *et al.* [115].

[21] Current research into the utilisation of polymer-clay nanocomposites aims at improving structural properties such as tensile strength [118] and thermal plasticity [119] as well as offering more bespoke timeframes for biodegradability.

[22] The E-waste recycling of printed circuit boards is a recent example [121].

> The principal task for engineers, designers, architects and natural scientists is to create products and systems that allow the extraction of a maximum amount of utility from the least possible quantity of nature for the longest possible time with the least possible use of space. In short: in products for sustainability, mass, space, need and energy have to be replaced by brainpower.

This begs the question of to what use will the product be applied and what are the material requirements [129]? In either situation, it suggests that in its broadest sense [130], dematerialisation considers reductions in base material consumption, whilst retaining, enhancing and maximising utility value.

One such example considers the microchip, where perceived utility value is high but product weight remains negligible [131]. However, secondary influences impact overall sustainability value[23] due to the ‘complementary assets’ [133] and consuming infrastructure needed to create the product in the first place, whether in small or massive quantities. These constraints might equally be applied to whole new ranges of ‘smart structures’ and technologies being developed for industrial and consumer applications [134–136], many of which fall within the armoury of the mechatronics systems developer or practitioner. However, their utility value must be verified in absolute terms through generic dematerialisation, if practicable, whilst retaining or improving functionality and minimising environmental impact. This calls for innovative procedures in systems development that explores complete life cycle and sustainability assessments as a priority and likewise for subsequent manufacturing and distribution in the marketplace.

2.9 Conclusion – From Responsible Design to Resource Recovery

For the mechatronics practitioner, the facility to incorporate whole life parameters into product developments and application should be seen as a fundamental objective in order to promote and secure sustainable system outcomes. The synergistic nature of the discipline, whereby the whole is perceived as greater than the sum of its parts, naturally leans towards integrated solutions. However, there are both positive and negative aspects of this synergy which can impact the quest for seeking sustainable mechatronic systems and products [137] such as reliability, maintainability and supportability; an example is the influence of structural fatigue and its damage consequences for whole life system performance [138]. Moreover, intentional ‘short-life’ product design, in order to encourage and simulate end user consumption, has no place in the eco-design philosophy [139].

In many ways, this poses yet another ethical dilemma for the system designer which had been alluded to some thirty years ago by Overby [140] who asked:

---

[23] Computer chips have a high environmental impact relative to weight [132] in terms of energy input throughout their manufacturing cycle.

> Is the idea of product design for a more sustainable future a matter of ethics, or is it simply a response to pragmatic circumstance – or is it some of both?

Pragmatism dictates that products and processes will evolve as newer functional technologies emerge, which may (or may not) be superior in performance terms from their predecessors, but are exploited to promote efficiency gains, manufacturing cost reductions, competitive advantage, etc. However, the system designer, and engineers in general, hold a duty of care and responsibility to ensure that technologies they prescribe meet ethical discourse criteria [141]. In order to ensure sustainable technology outcomes [142], engineers should ask themselves which types of situations require ethical reflection, and to what extent they should assume moral responsibility in the practice of their profession?. This can be summarised in terms of the sometimes onerous obligations placed on engineers to protect both the environment and public interest, where Alpern [143] declared:

> Engineers have a duty to make personal sacrifices in calling attention to defective design, questionable tests, dangerous products, and so on…

Thus, sustainable engineering incorporates ethical, social and ecological dimensions into the design of products and processes that will benefit society in general, and environmental imperatives in particular. By invoking not only moral questions of 'fitness for purpose', fundamental issues of environmental impact assessment, lifecycle thinking, preventing waste, minimising the depletion of natural resources and so on, in a holistic manner [144], also holds sway. This philosophy then aggregates with the Brundtland dictum of development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

For the design engineer and, more particularly, the mechatronic system developer, there are now a growing number of online resource tools available to deal with these challenging issues [145, 146] as well as hardcopy sources for application specific areas of design and manufacturing for sustainable development; examples include [147–149]. However, of all the design and application challenges that the developer faces, life cycle assessment (LCA) perhaps poses the most arduous of tasks since it incorporates many contrasts in adaptation and interpretation that can extend from sustainable consumption and resource recovery through self-disassembling products, to products that are never discarded [150]. Moreover, the now accepted standard approach to LCA tends to be directed downwards towards lower system levels resulting in optimised components within products rather than optimised products within their surroundings [151]. It is therefore necessary to invoke the broader perspective of industrial eco-systems [152][24] which Tibbs [154] attributes to being:

---

[24] Frosch and Gallopoulos, in their seminal article [153], introduced the notion of the industrial ecosystem which would function as an analogy to biological ecosystems, that is, '*plants synthesise nutrients that feed herbivores, which in turn feed a chain of carnivores whose wastes and bodies eventually feed further generations of plants.'*

> ...a logical extension of life-cycle thinking, moving from assessment to implementation. They involve 'closing loops' by recycling, making maximum use of recycled materials in new production, optimising use of materials and embedded energy, minimising waste generation, and revaluating 'wastes' as raw material for other processes.

Naturally, end of life treatment for products and processes is only a reactive response to considerations which should be addressed much earlier in the formation and manufacturing phase (and preferably from the design stage [155]), particularly material flows [156], dematerialisation [157] and energy flows (during configuration and anticipated lifetime usage) [158]. Nonetheless, the designer may be constrained by the path dependent nature of technology evolution [159, 160], whereby complex technologies become interactive and dependent upon the availability of complementary technologies[25] for their final system integration [162]. However, technological evolution often provides for many step change enhancements over predecessor technologies. They can result in substantial reductions in material consumption and product configuration complexity without loss of functionality and, in some instances, additional functional improvement. Two recent promising examples are a '$10 microscope' based on opt-fluidics and optics [163] and a 'bionic eye' based on compressible silicon optoelectronics [164][26]. Both developments appear to offer substantial utility value combined with significant dematerialisation, although it remains unclear whether the associated complementary technologies needed contribute an overall sustainability improvement.

For the most part, the concept of environmentally benign and optimally sustainable product outcomes remains a pipe dream, and the system developer will be forced to accommodate contingency for end of life handling provision (particularly under legislative directives, such as WEEE, etc.). Nonetheless, there are some *inter alia* assessment criteria that can be called upon to delay the advancement of end of life provision such as incorporating reliability [165] and maintainability [166] into the design evaluation process as well as attempting to 'future proof' or at least seek to predetermine useful product life [167]. Beyond this, the designer will need to apply an armoury of techniques and disassembly modelling for recycling and reuse [168]. This then paves the way to deal with resource recovery in a structured manner when applied to product and material cycles [169].

Mechatronic and IT-based products and systems, particularly those in the consumer domain, tend to have shorter life spans nowadays and, as such, accelerate the urgency to accommodate 'mass' resource recovery [170, 171]. However, resource recovery also creates a dilemma in decisions affecting the extent to which products can be repaired, reconditioned, remanufactured or

---

[25] These are technological assets which are peripheral to the main 'innovation' thrust, but may [nonetheless] prove vital to complement and support 'sustainability' (*sic*) of the development programme. They may also require some adaptation to ensure 'fitness for purpose' which is typically found in mechatronic systems' [161].

[26] Both developments were reported in the national and international press during 2008.

recycled. Moreover, new and emerging technologies tend to undermine attempts to optimise complete resource recovery for existent product stocks due to obsolescence. It would seem, therefore, that remanufacturing appears to offer the best strategy for mitigating unsustainable outcomes. For example, 'it enables the embodied energy of virgin production to be maintained' [172], although the full societal benefits will not be realised unless provision for remanufacturing is incorporated into the product development process in the first place [173].[27]

Looking further beyond 'end of product life' strategies is a wider socio-economic issue [176] and one that requires a radical approach to triple bottom line enquiry, particularly in terms of material selection [177]. Above all, however, is the need to adopt a systems thinking approach in order to push the sustainability agenda forward [178] and one which should sit well with the integrated and innovative nature of the mechatronics discipline. Thus, the connectivity between sustainability and innovation becomes a dominant theme [179] which can either facilitate or present barriers to sustainable futures [180]. Environmental technologies will make way for sustainable technologies where 'environmental performance considerations will be fully integrated with economic, social and other operational issues so that the system as a whole is sustainable' [181], *The Triple Bottom Line*.

References

1. Carson R (2000) Silent Spring. Penguin Classics, London.
2. Commoner B (1972) The Closing Circle: Confronting the Environmental Crisis, Jonathan Cape, London.
3. Dubos R, Ward B (1972) Only One Earth: The Care and Maintenance of a Small Planet. Penguin, Harmondsworth.
4. Meadows DH *et al.* (1974) The Limits to Growth, Pan Books, London.
5. Schmidheiny S (1992) Changing Course: A Global Business Perspective on Development and the Environment, MIT Press.
6. Elkington J (1999) Cannibals with Forks: The Triple Bottom Line of 21st Century Business, Capstone Publishing, Oxford.
7. Department of Trade and Industry (1999) Science and Innovation Strategy: Consultation Paper, DTI, London.
8. Council for Science and Technology (2000) Technology Matters: Report on the exploitation of science and technology by UK business, Department of Trade and Industry, London, Annex C.
9. Charter M, Clark T (2007) Sustainable Innovation. Centre for Sustainable Design, University of Surrey: 9.
10. Elliott C, Dearsley P (2007) Creating systems that work: Principles of engineering systems for the 21st century. The Royal Academy of Engineering:14.

[27] A typical application of mechatronic remanufacturing in automotive components can be found in Steinhilper *et al.* [174] together with 'Design for Remanufacture Guidelines' augmented by UK industrial case-based examples [175].

11. Alper J (1993) EEG+MRI: A sum greater than the parts, Science, J. American Assoc. for the Advancement of Science) y, **261** (5121):529–633.
12. Sourceforge, Bioelectromagnetism MATLAB toolbox www.eeg.sourceforge.net/bioelectromagnetism.html
13. So EL (2000) Integration of EEG, MRI, and SPECT in Localizing the Seizure Focus for Epilepsy Surgery. Epilepsia, 41 (Suppl. 3):548–554.
14. Bosch Safety Network, Field Guide to Automotive Technology, www.autofieldguide.com/articles/wip/0705wip09.html
15. De Lange, R. (2007) Intelligent Safety Systems Integrating Active and Passive Safety. 7th European Vehicle Passive Safety Conf., Maastricht:20 www.passivesafety.com/06_publications/proceedings.html
16. Vittorio SA (2001) MicroElectoMechanical Systems. CSA http://csa.com/discoveryguides/mems/overview.php
17. Pons JL (2005) Emerging Actuator Technologies: A Micromechatronic Approach. Wiley, UK.
18. Madou M (2002) Fundamentals of Microfabrication: The Science of Miniturization. 2nd ed., CRC Press.
19. Berkhout F, Green K (2002) Managing Innovation for Sustainability: The Challenge of integration and Scale, Int. J. of Innovation Management, **6** (3):227–232
20. Elzen B, Geels FW, Green K (Eds.) (2004) System Innovation and the Translation to Sustainability: Theory, Evidence and Policy. Edward Elgar, UK.
21. Kelly P *et al.* (1986) Introducing Innovation. Product Design and Technological Innovation (Eds. Roy R, Wield D), Open University Press, UK.
22. Godin B (2006) The Linear Model of Innovation: The Historical Construction of an Analytical Framework. Project on the History and Sociology of STI Statistics: Working Paper 30, Science, Technology and Human Values, **31** (6): 639–667
23. Rothwell R (1992) Successful industrial innovation: critical factors for the 1990's. R&D Management, **22**(3):.236
24. Vesilind PA, Gunn AS (1998) Engineering, Ethics, and the Environment. Cambridge University Press, UK.
25. Searing DR, Rabins MJ (1999) Ethics in Product Design. Mechatronics in Engineering Design and Product Development (Eds. Popovic D, Vlačić L), Marcel Dekker, New York:585–606.
26. Goldemberg J *et al.* (1988) Energy for a Sustainable World. Wiley Eastern, New Delhi, India:85–93
27. Gerbens-Leens PW, Hoekstra AY (2008) Business Water Footprint Accounting: A tool to assess how production of goods and services impacts on freshwater resources worldwide. UNESCO-IHE Institute for Water Education, Delft, March http://www.waterfootprint.org/Reports/Report27-BusinessWaterFootprint.pdf
28. Rosenburg N (1994) Exploring the Black Box: Technology, economics, and history, Cambridge University Press,:188
29. Martin MJC (1984) Managing Technological Innovation and Entrepreneurship. Reston Publishing:106–117
30. Martin MJC (1994) Managing Innovation and Entrepreneurship in Technology-Based Firms. Wiley, New York:145–148
31. Herkert JR, Farrell A, Winebrake JJ. (1996) Technology Choice for Sustainable Development. IEEE Technology and Society Magazine, Summer
32. Bradbury JAA (1989) Product Innovation: Idea to Exploitation. Wiley, UK.
33. Dodgson M (2000) The Management of Technological Innovation: An International and Strategic Approach, Oxford University Press, UK.
34. Rogers EM (1995) Diffusion of Innovations 4th ed. The Free Press, New York.
35. Tether B (2003) What is Innovation?: Approaches to Distinguishing New Product and Processes from Existing Products and Processes. Centre for Research on Innovation and Competition (CRIC Working Paper No. 12), University of Manchester, August

36. Innovation: Key Innovation concepts & definitions, Institute for Manufacturing, Cambridge University, http://www.ifm.eng.cam.ac.uk/ctm/idm/innovation/default.html
37. Millbank JH (2002) A Framework for Technology and Knowledge Transfers as Primary Drivers for Competitive Advantage. 2002 IEEE Int. Engineering Management Conf., Cambridge:410
38. Rogers EM, Valente TW (1991) Technology Transfer in High technology Industries. Technology Transfer in International Business (Eds. Agmon T, Von Glinow MA), Oxford University Press, UK:104
39. Voß J-P, Truffer B, Konrad K (2006) Sustainability Foresight: reflective governance in the transformation of utility systems. Reflective Governance for Sustainable Development (Eds. Voß J-P *et al.*), Edward Elgar, UK:165–167
40. Cuhls K (2003) From forecasting to foresight processes – new participative foresight activities in Germany. J. of Forecasting, Special Issue on Technology Foresight, **22** (2-3):93–111.
41. Martin BR, Irvine J (1989) Research Foresight: Priority-Setting in Science. Pinter, London.
42. Martino JP (1992) Technological Forecasting for Decision Making. McGraw-Hill, New York.
43. Twiss BC (1992) Forecasting for Technologists and Engineers. Peter Peregrinus, UK.
44. Inzelt A, Coenen R (1996) Introduction. Knowledge, Technology Transfer and Foresight (Eds. Inzelt A, Coenen R), Kluwer, pXVI/XVII.
45. Coates JF (2001) Future and Technology Assessment Research for Business Clients. Inaugural Meeting of the Center for Impact Assessment Studies and Forecasting, Warsaw, October, josephcoates.com/pdf_files/263_Future_Research_for_Biz.pdf
46. Porter AL (1995) Technology Assessment, Impact Assessment. Int. Association for Impact Assessment, **13**, Summer
47. Braun E (1998) Technology in Context: Technology Assessment for Managers, Routledge, London.
48. Van den Erde *et al.* (1998) Traditional and Modern Technology Assessment: Towards a Toolkit – A Research Methodology and Learning Strategy for Social Impact Assessment. Technological Forecasting and Social Change, **58** (1):5–17.
49. Gausemeier J (2005) From Mechatronics to Self-Optimization: A New Approach to Shape the Future of Mechanical Engineering. Enabling Technologies for the New Knowledge Society, 3rd Int. Conf. on Information & Communication Technology, Cairo www.hni.uni-paderborn.de/uploads/media/Manuskript_ICICT_Kairo.pdf
50. Fey VR, Rivin EI (1999) Guiding Technological Evolution. TRIZ Journal, January www.triz-journal.com/archives/1999/01/c/default.asp?action=print
51. Kuntze U (1999) Resource-Efficient Technologies: Results and Methodological Aspects of the German Delphi ’98 Survey. Proc. of OECD Technology Foresight and Sustainable Development Workshop, Budapest:26–48
52. Cuhls K, Blind K, Grupp H. (2002) Innovations for our Future. Physica-Verlag, Heidelberg, Germany.
53. Georghiou L (2001) Third Generation Foresight–Integrating the Socio-economic Dimension. Proc. Int. Conf. on Technology Foresight, National Institute of Science and Technology Policy (NISTEP), Japan www.nistep.go.jp/archiev/ftx/eng/mat077e/html/mat0771e.html
54. Borup M (2005) Sustainability requirements for foresight–A suggestion of a framework of principles. Int. Conf.: Foresight Management in Corporations and Public Organisations – New Visions for Sustainability, Helsinki www.risoe.dk/rispubl/SYS/syspdf/sys_2005.pdf
55. Sloman A (1978) The Computer Revolution in Philosophy: Philosophy Science and Models of Mind, The Harvester Press, UK.
56. Sellen AJ, Harper RHR (2002) The myth of the paperless office. MIT Press, MA.
57. Riley P (2001) E-mail’s Contribution to Total Paper Consumption on the U.C. Berkley Campus: An Investigation of the Printing Behavior of both Students and Staff www.socrates.berkley.edu/~es196/projects/2001final/Riley.pdf

58. Blumentritt R, Johnson R (1999) Towards a Strategy for Knowledge Management. Technology Analysis and Strategic Management, **11**(3):287–300.
59. Rowland F (1999) Diffusion of information across the sciences. Communicating Science: Professional Contexts (Eds. Scanlan E *et al.*), Routledge:155
60. Davenport TH, Prusak L (1998) Working Knowledge: How Organisations Manage What They Know. Harvard Business School Press:88–106 www.nwlink.com/~donclark/knowledge/vv.html
61. Whittaker S, Sidner C (1996) Email overload: exploring personal information management of email. Proc. Conf. on Computer Human Interaction, ACM Press, NY:276–283
62. Quah DT (1999) The Weightless Economy in Growth. The Business Economist, **30**(1):40–53
63. Huws U (1999) Material World: the Myth of the 'Weightless Economy'.Socialist Register, Merlin Press/Monthly Review Press
64. Fuchs C (2008) The implications of new information and communication technologies for sustainability. J. of Environment, Development and Sustainability, **10**(3):291–309.
65. Munn A *et al.* (2007) Computer Industry Impacts on the Environment and Society. University of Michigan, sitemaker.umich.edu/section002group3/home
66. Iliasov A (2008) Towards Rigorous Engineering of Resilient Pervasive Systems. 7th European Dependable Computing Conf. (EDCC-7), Kaunas
67. Koomey JG (2007) Estimating Total Power Consumption by Servers in the U.S. and the World. Stanford University/Lawrence Berkeley National Laboratory blogs.business2.com/greenwombat/files/serverpowerusecomplete-v3.pdf
68. Patel CD (2003) A Vision of Energy Aware Computing from Chips to Data Centers. Int. Symposium on Micro-Mechanical Engineering (JSME), December
69. Princen T *et al.* (Eds.) (2002) Confronting Consumption, MIT Press:4.
70. O'Brien M (2007) A Crisis of Waste? Understanding the Rubbish Society. Routledge
71. Cooper T (2007) Challenging the 'refuse revolution': war, waste and the rediscovery of recycling, 1900-50. Historical Research, Blackwell
72. Waste online (2004) History of waste and recycling information sheet www.wasteonline.org.uk/resources/InformationSheets/HistoryofWaste.htm
73. Fisk G (1973) Criteria for a Theory of Responsible Consumption. J. of Marketing, **37:**24–31, www.jstor.org/pss/1250047
74. Murphy J (Ed.) (2007) Governing Technology for Sustainability, Earthscan, London.
75. Spangenberg JH (2004) The Society, its products and the environmental role of consumption. The Ecological Economics of Consumption (Eds. Reisch LA, Røpke I), Edward Elgar:32–59
76. Faninger G (2003) Towards sustainable development in Austria: renewable energy contributions. Mitigation and Adaption Strategies for Global Change, **8**(2):177–188
77. BMVIT (2008) Technologies for Sustainable Development, Federal Ministry for Transport, Innovation and Technology, Vienna www.bmvit.gv.at/en/innovation/sustainable.html
78. Slade G (2006) Make a Break: Technology and Obsolescence in America. Harvard University Press.
79. Ehrenfeld D (1999) The Coming Collapse of the Age of Technology, Tikkun (A Bimonthly Jewish Critique of Politics, Culture & Society), Jan/Feb www.tikkun.org/magazine/index.cfm/action/tikkun/issue/tik9901/article/990111a.html
80. Josias C *et al.* (2004) Component Obsolescence Risk Assessment. Proc. of the 2004 Industrial Engineering Research Conference (IERC), Houston www.enme.umd.edu/ESCML/ObsSGER/IERC2004-Josias-Terpenny-McLean-376.pdf
81. Burns B (2003) Improved Sustainable Product Life Options for Innovation through the re-evaluation of factors affecting Product Obsolescence. Sustainable Innovation 03, 8th Int. Conf. Towards Sustainable Product Design (CfSD), Stockholm
82. Feldman K, Sandborn P (2007) Integrating Technology Obsolescence Considerations into Product Design Planning. Proc. of the ASME 2007 Int. Design Engineering Technical

Confs. & Computers and Information in Engineering Conf., Las Vegas www.enme.umd.edu/ESCML/Papers/DFMLC-35881_Final_Manuscript.pdf
83. Birchall D, Tovstiga G (2002) Future Proofing, Capstone
84. Birch S (2005) Volvo 3CC is future-proofed. Automotive Int., **113**(4):34.
85. Birchall D Tovstiga G (2005) Capabilities for Strategic Advantage: Leading Through Technological Innovation. Palgrave Macmillan:121–127
86. Petrick IJ, Echols AE (2005) Technology roadmapping in review: A tool for making sustainable new product development decisions. Technological Forecasting and Social Change, **71**(1-2):81–100
87. Farrukh C *et al.* (2003) Technology roadmapping: linking technology resources into business planning. Int. J. of Technology Management, **26**(1):2–19
88. Witt U (2001) Consumption, demand, and economic growth – an introduction. Escaping Satiation: The Demand Side of Economic Growth (Ed Witt U), Springer Velag:1–12
89. Kash DE, Rycroft, R (2002) Emerging Patterns of Technological Innovation, Technological Forecasting and Social Change, 69(6), July, 581–606
90. Kash DE, Rycroft RW (2003) To Manage Complex Innovation, Ask the Right Questions. Research-Technology Management, **46**(5):29–33
91. Hobday M (1998) Product complexity, innovation and industrial organisation. Research Policy, **26**(6):689–710
92. Prencipe A (2000) Breadth and depth of technological capabilities in CoPS: The case of the aircraft engine control system. Research Policy, **29**(7-8): 895–911
93. Vries MJ (2005) Ethics and the complexity of technology: a design approach. Int. Symp. Assoc. for Reformational Philosophy in the Netherlands, Workshop Session III
94. Loureiro G *et al.* (Eds.) (2007) Complex Systems Concurrent Engineering: Collaboration, Technology Innovation and Sustainability, Springer Verlag, Germany.
95. Hofer AP, Halman JIM (2004) Complex products and systems: Potential from using layout platforms. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, **18**(1):55–69
96. Lee BC (2007) Flattening the World Efficiently: Digital Sustainability for the 21st Century. St. Gallen Symposium: The Power of Natural Resources
97. Parker R (2008) New Phenon CPU's Announced from AMD. Techwatch, 28 March
98. Ayres D (2008) Reducing Design Complexity at Lucent. Design News for Mechanical and Design Engineers, Reed Business Information
99. PTC White Paper 3453 (2008) Reducing Complexity: Synchronizing Software & Hardware Development. Parametric Technology Corporation, MA www.ptc.com/WCMS/files/72260/en/3453_Red_Comple_WP_Final.pdf
100. Ashby MF (2005) Eco-selection: environmentally informed material choice, IMechE Seminar Proc.: Materials for a Greener Environment – Reduce, Reuse, Recycle and Recover, London
101. Ford (2008) Design for Sustainability: Choosing More Sustainable Materials, Sustainability Report 2007/8, www.ford.com/microsites/sustainability-report-2007-08
102. Rebitzer G *et al.* (2006) Design for the Environment in the Automotive Sector with the Material Selection Tool euroMat www.euromat-online.de/englisch/Unterseiten-engl/method.html
103. Wolf O (2005) Techno-economic Feasibility of Large-scale Production of Bio-based Polymers in Europe. Technical Report EUR 22103 EN, European Commission, December
104. Clark JH, Hardy JJE (2004) Towards Sustainable Chemical Manufacturing: Polylactic Acid – A sustainable polymer? Sustainable Development in Practice: Case Studies for Engineers and Scientists (Eds. Azapagic A *et al.*), Wiley:259
105. Goodship V (2007) Introduction to Plastics Recycling (2nd Edition), Smithers Rapra
106. Thiriez A, Gutowski T (2006) An Environmental Analysis of Injection Molding. Proc. of the 2006 IEEE Int. Symp. on Electronics and the Environment:195–200

107. Fisher MM *et al.* (2005) Energy Recovery in the Sustainable Recycling of Plastics from End-of-Life Electrical and Electronic Products. IEEE Int. Symp. on Electronics & the Environment, New Orleans
108. Hunt RG *et al.* (1992) Resource and environmental profile analysis: A life cycle environmental assessment for products and procedures. Environmental Impact Assessment Review, **12** (3):245–269.
109. Lundquist L *et al.* (2000) Life Cycle Engineering of Plastics: Technology, Economy and the Environment, Elsevier
110. O'Neill TJ (2002) Life Cycle Assessment and Environmental Impact of Polymeric Products. Rapra Review Reports **13**(12), Smithers Rapra Technology Ltd.
111. Azapagic A *et al.* (2003) Polymers, the Environment and Sustainable Development, Wiley
112. Tucker N, Johnson M (2004) Low Environmental Impact Polymers, ChemTec Publishing, Canada.
113. Bastioli C (2005) Handbook of Biodegradable Polymers, ChemTec Publishing, Canada.
114. Delaplace M, Kabouya H (2001) Some considerations about interactions between regulation and technological innovation: the case of a sustainable technology, biodegradable materials in Germany, European J. of Innovation Management, **4**(4):181
115. Carlsson B *et al.* (2002) Innovation systems: analytical and Methodological issues. Research Policy, **31**(2):235
116. Nakiri T *et al.* (2007) Development of Electrical Wire Using Biodegradable Polymer. IEEE Trans. on Industrial Applications, **43**(4):1069–1074
117. Rosato D (2008) Novel Bioplastic Consumer Product Developments. Omnexus, www.omnexus.com/plastic-channels/green-bio-plastics/editorials.aspx?id=18461
118. Okada K *et al.* (2003) Properties and particles dispersion of biodegradable resin/clay nanocomposites, Korea-Australia Rheological Journal, **15**(1):43–50
119. Ikeo Y (2006) Nano clay reinforced biodegradable plastics of PCL starch blends. Polymers for Advanced Technologies, **17**(11-12):940–944
120. Greiner Environmental (2002) Environmental, Health and Safety Issues in the Coated Wire and Cable Industry (Technical Report No. 51), Toxic Use Reduction Institute, University of Massachusetts Lowell, turi.org/content/download/913/4501/file/Wire_Cable_TechReport.pdf
121. Leung AOW (2008) Heavy Metals Concentrations of Surface Dust from e-Waste Recycling and Its Human Health Implications in Southeast China, Environmental Science & Technology, American Chemical Society, **42**(7):2674–2680.
122. European Union (2002) Directive of the European Parliament on the Restriction of the Use of Certain Hazardous Substances (2002/95/EC) eu.int/comm/environment/docum/00347_en.htm
123. European Union (2002) Directive on Waste Electrical and Electronic Equipment (2002/96/EC), ec.europa.eu/environment/waste/weee/index_en.htm
124. Puttlitz KJ, Stalter KA (Eds.) (2004) Handbook of Lead-Free Solder Technology for Microelectronic Assemblies, Marcel Dekker
125. Dittes M *et al.* (2003) Tin Whisker Formation – Results, Test Methods and Countermeasures, 53rd IEEE Electronic Components and Technology Conf.: 822–826
126. Galyon GT, Gedney R (2004) Avoiding Tin Whisker Reliability Problems, Circuits Assembly, August:26–31
127. Weaver PM, Rotmans J (2006) Integrating Sustainability Assessment: What? Why? How? Matisse Working Paper 1, matisse-project.net/projectcomm/uploads/tx_article/Working_Paper_1_03.pdf
128. Ritthoff M *et al.* (2002) Calculating MIPS: resource productivity of products and services, Wuppertal Spezial 27e, Wuppertal Institute for Climate, Environment and Energy, Wuppertal
129. Schmidt-Bleek F (2004) No Sustainability without Dematerialisation, (Part based text for) 2004 Report of the Future Council of the German State of North Rhine-Westfalia

130. Von Weizsäcker EU (1998) Dematerialisation. Managing a Material world: Perspectives in Industrial Ecology (Eds. Vellinga P *et al.),* Kluwer:45–54
131. Williams ED *et al.* (2002) The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices, Environmental Science & Technology. American Chemical Society, **36**(12):5504–5510
132. Environmental Literacy Council (2008) Computer Chip Life Cycle, 3 April, enviroliteracy.org/article.php/1275.html
133. Teece DJ (1986) Profiting from technological innovation: implications for integration, collaboration, licensing and public policy. Research Policy, **15**(6), 285–305
134. Worden K. *et al.* (2003) Smart Technologies. World Scientific Publishing, Singapore.
135. Spencer Jr BF *et al.* (Eds.) (2007) World Forum on Smart Materials and Smart Structures Technology: Proc. of SMSST'07, Routledge
136. Schwartz M (2008) Smart Materials. CRC Press, Boca Raton, FL. (Forthcoming)
137. Tähemaa T, Reedik V (2001) Prognosis of the Competitive Dependability of Mechatronic Products. Design Methods for Performance and Sustainability (WDK 28) (Eds. Culley S *et al.*), Proc. of 13th Int. Conf. on Engineering Design, Professional Engineering Publishing:3–10
138. Giudice F *et al.* (2006) Product Design for the Environment. CRC Press, Boca Raton: 251–276
139. Baynes A *et al.* (2001) Environmental Technologies and their Business Drivers. Sustainable Solutions: Developing Products and Services for the Future (Eds Charter M, Tischner U), Greenleaf Publications:340–348
140. Overby CM (1980) Product Design for a Sustainable Future: A Matter of Ethics? American Society for Engineering Education (ASEE) Annual Conf. Proc.:511–519 www.article9society.org/pp-14.pdf
141. Stahl BC (2000) Responsibility for Technological Development by Discourse. www.cse.dmu.ac.uk/~bstahl/publications/2000_Resp_tech_dev.pdf
142. Grunwald A (2001) The application of ethics to engineering and the engineer's moral responsibility: Perspectives for a research agenda. Science and Engineering Ethics, **7**(3):415–428
143. Alpern KD (1983) Moral Responsibility for Engineers, Business and Professional Ethics Journal, 2:39–48
144. Abraham MA (2005) Principles of Sustainable Engineering. Sustainability Science and Engineering: Defining Principles (Ed Abrahams MA), Elsevier Science:3–10
145. EcoDesign (2005) A Guide for EcoDesign Tools. 2nd Edition, August, www.ecodesignarc.info/servlet/is/413/
146. Kurk F, McNamara C (2006) Better by Design – An Innovation Guide: Using Design Solutions, Minnesota Pollution Control Agency, St. Paul www.engineeringpathway.com/ep/k12/BetterByDesign_2006.pdf
147. Allwood JM (2005) Distributed localised production as a strategy for sustainable manufacturing. 4th Int. Conf. on Design and Manufacturing for Sustainable Development, Newcastle
148. Baeyens J (2005) Challenges for Design Engineers in Sustainable Engineering. 5th Int. Conf. on Design and Manufacture for Sustainable Development, Loughborough
149. Tischner U, Charter M (2001) Sustainable Product Design. Sustainable Solutions: Developing Products and Services for the Future (Eds. Charter M, Tischner U), Greenleaf Publishing:118–137
150. Brissaud D *et al.* (2006) Innovation in Life Cycle Engineering and Sustainable Development, Springer
151. Bey N, McAloone T (2006) From LCA to PSS – Making leaps towards sustainability by applying product/service-system thinking in product development. Proc. of 13th Int. Conf. on Life Cycle Engineering (LCE 2006), Leuvin:571–576

152. Jelinski LW *et al.* (1992) Industrial Ecology: Concepts and Approaches. Proc. National Academy of Science (Colloquium Paper, NAS, Washington, DC. 20/21 May, 1991), 89, February:793–797
153. Frosch RA, Gallopoulos NE (1989) Strategies for Manufacturing. Scientific American, **189**(3):144–152
154. Tibbs H (1993) Industrial Ecology: An Environmental Agenda for Industry, Global Business Network, p.10. www.hardintibbs.com/pdfs/gbn_ecology.pdf
155. Gehin A *et al.* (2008) A tool to implement sustainable end-of-life strategies in the product development phase. J. for Cleaner Technology, **16**(5):566–576
156. Allen DT (2004) An Industrial Ecology: Material Flows and Engineering Design. Sustainable Development in Practice (Eds. Azapagic A *et al.),* Wiley
157. Wernick IK *et al.* (1997) Materialization and Dematerialization. Technological Strategies and the Human Environment (Eds. Ausubel J, Langford HD), National Academy Press: 135–156
158. Ehrenfeld JR (1997) Industrial Ecology: a framework for product and process design. J. of Cleaner Production, **5**(1/2):87–95
159. Berkhout F (2002) Technological regimes, path dependency and the environment. Global Environmental Change, **12**(1):1–4
160. Sandén B (2004) Technology Path Assessment for Sustainable Technology Development. Innovation: Management, Policy & Practice, 6 (Corporate Sustainability: Governance, Innovation Strategy, Development & Methods):316–330
161. Millbank JH (2001) Strategies for the Effective Management of Technology Transfer. M.Sc., Dissertation, University of Salford, UK:49
162. Rycroft RW, Kash DE (2002) Path Dependence in the Innovation of Complex Technologies. Technology Analysis & Strategic Management, **14**(1):28
163. Psaltis D *et al.* (2006) Developing optofluidic technology through the fusion of microfluidics and optics. Nature (Insight Review), 427:381–386.
164. Ko HC *et al.* (2008) A hemispherical electronic eye camera based on compressible silicon optoelectronics. Nature (Letters), 454:748–753
165. Dhillon BS (2007) Design for Reliability. Environmentally Conscience Mechanical Design (Ed. Kutz M), Wiley:161–184
166. Okogbaa OG (2007) Design for Maintainability. In:[165].
167. Kara S (2008) Assessment of products for useful life. CIRP Annuls – Manufacturing Technology, **57**(1):1–4
168. Lambert AJD, Gupta SM (2005) Disassembly Modeling for Assembly, Maintenance, Reuse, and Recycling. CPC Press
169. Seliger G (Ed.) (2007) Sustainability in Manufacturing: Recovery of Resources in Product and Material Cycles, Springer Verlag, Germany.
170. Goggin K, Browne J (2000) Towards a taxonomy of resource recovery for end-of-life products. Computers in Industry, **42**(2/3):177–191
171. Yonghua X *et al.* (2008) Role of Resource Recovery of Waste Machinery and Electronic Products in Sustainable Development. Int. Conf. on Bioinformatics and Biomedical Engineering (ICBBE 2008), Shanghai:4333–4335
172. King AM *et al.* (2005) Reducing waste: repair, recondition, remanufacture or recycle? Sustainable Development, **14**(4):257–267
173. Nasr N, Thurston M (2006) Remanufacturing: A Key Enabler to Sustainable Product Systems. Proc. of the 13th CIRP International Conference on Life Cycle Engineering, Engineering (LCE 2006), Leuvin:15–18
174. Steinhilper R *et al.* (2006) Product and Process Assessment for Remanufacturing of Computer Controlled Automotive Components. In: [169]
175. Ijomah WL *et al.* (2007) Development of robust design-for-remanufacturing guidelines to further the aims for sustainable development Int. J. of Production Research, **45**(18/19):4513–4536

176. Carmichael C (2003) A Primer on Sustainable Technology and Development. ISTD, Georgia Institute of Technology, ww.sustainable.gatech.edu/resources/ISTDPrimer_1_7_02.pdf
177. Ljungberg LY (2007) Materials selection and design for development of sustainable products. Materials & Design, **28**(2):466–479
178. Foxon TJ (2006) Applying systems thinking and practice for promoting sustainable innovation. (Science Policy Research Unit) SPRU 40th Anniversary Conf. University of Sussex
179. Lehmann-Waffenschmidt M (Ed.) (2007) Innovations Towards Sustainability: Conditions and Consequences, Physica-Verlag, Heidelberg.
180. Hines F, Marin O (2004) Building innovations for sustainability: 11th Int. Conf. of the Greening of the Industry Network (Editorial), Business Strategy and the Environment, **13**(4):201–208
181. Halls S (2006) Technology transfer and uptake of environmentally sound technologies. The Int. Handbook on Environmental Technology Management (Eds. Marinova D *et al.*), Edward Elgar Publishing:175

http://www.springer.com/978-1-84996-079-3

Mechatronics in Action
Case Studies in Mechatronics - Applications and Education
Bradley, D.; Russell, D.W. (Eds.)
2010, XVII, 263 p., Hardcover
ISBN: 978-1-84996-079-3