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DEVELOPMENT OF A FRAMEWORK FOR ASSESSING SUSTAINABILITY IN NEW PRODUCT DEVELOPMENT

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ABSTRACT
The area of sustainability in business is crowded with discussion and tools that are geared towards change at the organisational level (e.g. Corporate Social Responsibility). At the product level, there is a predominance of work focusing on environmental sustainability (e.g. Design for Environment). This work addresses the multiple aspects of sustainability that are involved in making decisions in new product development (NPD). A framework is proposed that maps different facets of sustainability against each stage of the product life cycle. This framework will provide the basis for an assessment tool to improve Design for Sustainability capabilities in NPD.

Keywords: Sustainability, New Product Design, Life Cycle

1 INTRODUCTION

Sustainability has become a buzzword in business over the last few years. As well as its growing popularity as a consumer concept, businesses are under mounting legal and commercial pressure to operate in a sustainable way [1]. Increasingly, firms are committed to sustainability policies and schemes, but it is often unclear whether these are effective [2]. Businesses that are developing new products face decisions pertaining to the sustainability of these products at the design phase – should sustainability considerations be designed into new products? And if so, on what basis?

The remainder of this paper will discuss sustainability considerations and their application during the process of new product design to optimise outcomes at the product level. This section introduces the topic and approach to the study. Section 2 presents a literature review of current work and techniques, leading to Section 3, which details the framework itself. The framework is discussed in section 4 and proposed further work is detailed in section 5.

1.1 Boundaries and assumptions
Sustainability considerations are necessarily macro-level issues; they impact our capacity as a global population to maintain the planet in a sustainable way. This means that considering sustainability at any level smaller than globally involves acknowledgement of impacts outside of the particular system of study. For example, studying the sustainability of a farm in the UK involves considering not only the farm itself, but also those who supply the farm, and those who supply them and so on. The net of considerations can be cast so wide that it becomes impossible to see the wood for trees, and change at any level is difficult to define. In this study, sustainability considerations are restricted to the product level. This is for two reasons:

1. The product is the unit of consideration at the design stage.
2. From a design perspective the product is the major tangible source of impact on outside systems.

The work considers new products from the point at which a decision to take them forward and manufacture them has been made. In other words, the framework is not designed to address decisions over whether or not a product should or should not be made, rather the issues that need to be addressed in designing it. This approach is, in some senses artificial as it separates the initial design activities from feasibility decisions, but the proposed framework is designed to provide information that feeds into the design process, not as a substitute for the design process itself.

This study does not refer to making the process of generating ideas sustainable, it refers to building sustainability considerations into the design and manufacture of new products themselves, in particular products that are physical objects, rather than services.

1.2 Design for sustainability

Design for X principles encourage the consideration of the downstream impacts of decision making that happens at the beginning of the design process. This early consideration of later consequences tackles the problem of the increasing difficulty and expense associated with implementing changes late in the design process. Design for X can encompass many issues, where 'X' relates to a downstream issue of potential consequence, for example, design for service, design for installation, design for repair etc. This mode of thinking allows designers to link specific needs to the design issues that they face [3].

There is plenty of work published in the literature on Design for Environment (DfE), in general though, much of the DfE work does not directly approach the social and economic aspects of sustainability; and there is less work on Designing for Sustainability as a whole (DfS). In other words, designing for sustainability is a larger field than DfE alone. This study aims to address this across all the major facets of sustainability using life cycle thinking, which is outlined in greater detail in Section 2 below.

1.3 Approach

The framework was initially built using considerations and principles taken from literature and mapped against the product life cycle. It was later refined using input from academic experts in the fields of sustainability, materials engineering and NPD. The refined version of the model will ultimately be used as the foundation for detailed case studies in industry, prior to developing an assessment tool for analysing business' sustainability capabilities in NPD.

2 LITERATURE REVIEW

2.1 Sustainability

Sustainability in new product development can be viewed as part of the wider research and practice field of sustainable development. This was defined by the World Commission on Environment and Development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [4]. Since then definitions of sustainability have evolved and reformed, but since the mid 1990s it has been widely accepted that sustainability is a multi-faceted concept, encompassing environmental, social and economic considerations [5]. These have become known as the 'three pillars' of sustainability.

Sustainability has shown an increasingly high profile in business over the last few years and it is now almost universally accepted as a goal [6]. Academic activity is also on the rise. Figure 1 gives an indication of the growing popularity of sustainability as a research topic using the number of papers in the SCOPUS online database that contain the word 'sustainability' in the title.

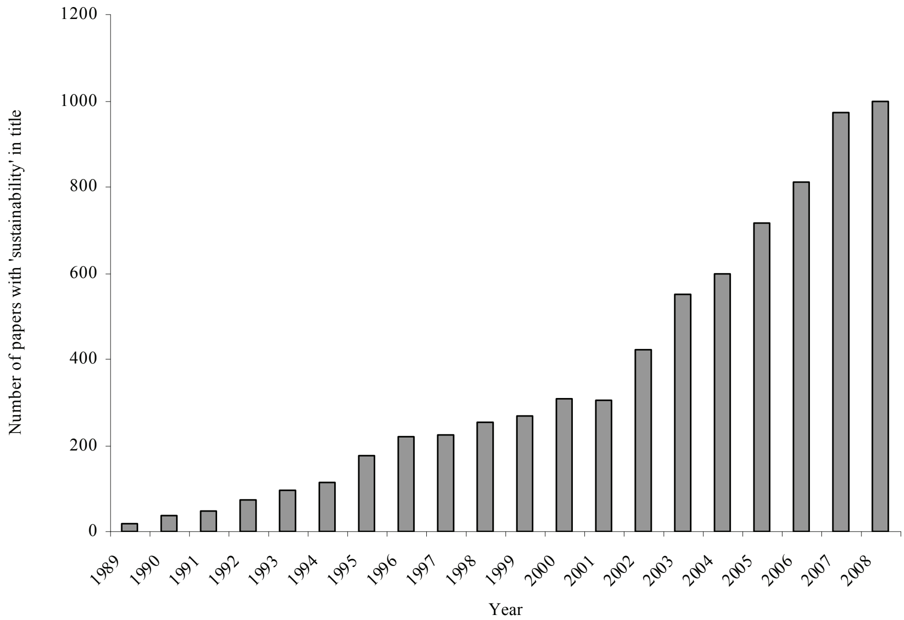

Figure 1 – Papers in SCOPUS database with 'sustainability' in the title

2.2 Approaches to sustainability

There is more than one way to approach sustainability and its assessment. Some approaches group two of the three pillars together, or they may favour one aspect of sustainability over the others. Other approaches treat all aspects equally. Below is a summary of common approaches to the concept of sustainability:

- 'Deep Green' theory holds that because a finite level of natural resources is available to the population, the primary priority is always to find ways to live within the natural constraints of the ecosystem [7]. This view is often represented by three concentric circles – the outermost signifying ecological considerations, the middle, social considerations and the centre, economic considerations.
- The 'Triple Bottom Line' (TBL) approach originated as an accounting principle that required businesses to identify actions against each of the three pillars of sustainability. Since then, this concept has evolved to become part of general sustainability theory and is now mostly identified with the classic 'three pillar' approach to sustainability. This is usually depicted as three overlapping circles, one representing each sustainability pillar. This conveys the idea that each of the pillars is of equal importance and that each overlaps with the others.
- Four part frameworks, that introduce another dimension to the traditional three pillar approach to sustainability (e.g. 'Institutional' used by the UN).

(Adapted from [6] and [8])

These approaches are well documented and apply largely to sustainability assessment at the project or business level. This study deals with designing for sustainability in new products. The design of new products is generally an activity undertaken by businesses, and this has implications for the choice of approach. This study takes a TBL approach to sustainability because:

- It makes a distinction between economic and social considerations (some other approaches group together as 'human' *versus* 'environmental') that is essential for viewing sustainability from a business standpoint.

- It allows parallel rather than sequential consideration of economic, social and environmental aspects, upon which later identification of trade offs and synergies depends.
- It allows for the condition that economic considerations have different drivers to social and environmental considerations (because businesses exist to make money) but that they must still be analysed in an integrated manner.
- Proposed fourth dimensions (institutional, cultural etc). are generally have less direct impact on business decision making.

Within the literature there is some criticism of sustainability assessments that adopt a TBL approach [8]. Pope *et. al.* [8] argue that a TBL approach is reductionist, and that dividing considerations as per the three pillars runs the risk of losing sight of synergies whilst favouring the exposure of conflicts. The argument follows that this results in sustainability outcomes that are less than the sum of their parts rather than, potentially, greater.

Whilst this may apply in some circumstances at the project level, at the product level, exposure of conflict between different sustainability considerations is both intentional and essential. Designers are expected to identify and solve (to a greater or lesser degree) these conflicts as part of the product development process. In addition, the framework outlined in this study is bidirectional in that it promotes both the identification of conflict and the identification of synergy.

In practice, the design of a new product will have to pass the ultimate test of viability (either on its own or as part of a company's broader strategy). This study does not exist to contest this point, rather to assist designers in optimising sustainability outcomes in new product development, given the constraints that exist.

2.3 Triple Bottom Line Sustainability

As discussed above a Triple Bottom Line approach divides sustainability considerations according to the three pillars: economic, social and environmental.

Environmental sustainability

Work by Daly and Cobb [9] is summarised by Goodland in [10]: 'Waste emissions from a project or action being considered should be kept within the assimilative capacity of the local environment, without unacceptable degradation of its future waste absorptive capacity or other important services. Rates of renewable resource inputs must be kept within regenerative capacities of the natural system that generates them. Depletion rates of non-renewable resource inputs should be set below the historical rate at which renewable substitutes were developed by human invention and investment.'

In a product engineering context, Vink et. al. [11] state that 'Environmental sustainability is about making products that serve useful market and societal functions with less environmental impact than currently available alternatives. Moreover, environmental sustainability necessarily implies a commitment to continuous improvement in environmental performance'. In practice, this involves using processes which reduce energy and material consumption via clean manufacturing and use, while maximizing the possibility for reuse and recycling through end of life strategies [1].

Economic sustainability

Goodland [10] [12] defines economic sustainability as the maintenance of (or the ability to maintain) stable monetary capital. At the level of the organisation, economic sustainability is simply how a company stays in business, measured in terms of growth and profit, and ultimately by its long term survival. Good financial performance is necessary for short term survival, but does not necessarily guarantee business in perpetuity, or positive outcomes for other types of sustainability (social or environmental) [13].

Social sustainability

A consensus definition for social sustainability is not forthcoming, probably since social phenomena are less tangible than economic or environmental outputs, and refer to both the individual and the collective. Ambiguity notwithstanding, social sustainability can be thought of as the maintenance of social capital [14]. Maintenance and renewal of this social capital is achieved by community interaction, shared values and equal rights. In the same way as economic or physical capital, social

capital depletes without investment and renewal. Costs of inadequate investment in social capital include violence and social breakdown and these factors inhibit social sustainability [9].
Social sustainability concerns within a business look to both internal factors (working conditions, wages, access to education etc.) and external factors (e.g. impact on those who live near the operating centres of the business). These extend as far as impact on intangibles such as culture and community. Major drivers for change in this area have included pressure from NGOs and introduction of human rights laws [15]. Social sustainability can be harder to measure in a business setting than environmental and economic sustainability since companies still seem reluctant to analyse their social impact in as fine detail [16].

2.4 Balancing sustainability considerations

The majority of academic and practitioner led work so far has focused on environmental sustainability. Figure 2 below shows the number of papers published between 1991 and 2008 with the words 'environmental sustainability', 'social sustainability' and 'economic sustainability' in the title that can be retrieved from the SCOPUS database online. Although this type of search result is a slightly blunt instrument, the graph clearly illustrates that far more material has been produced on environmental sustainability than in either of the other two major domains.

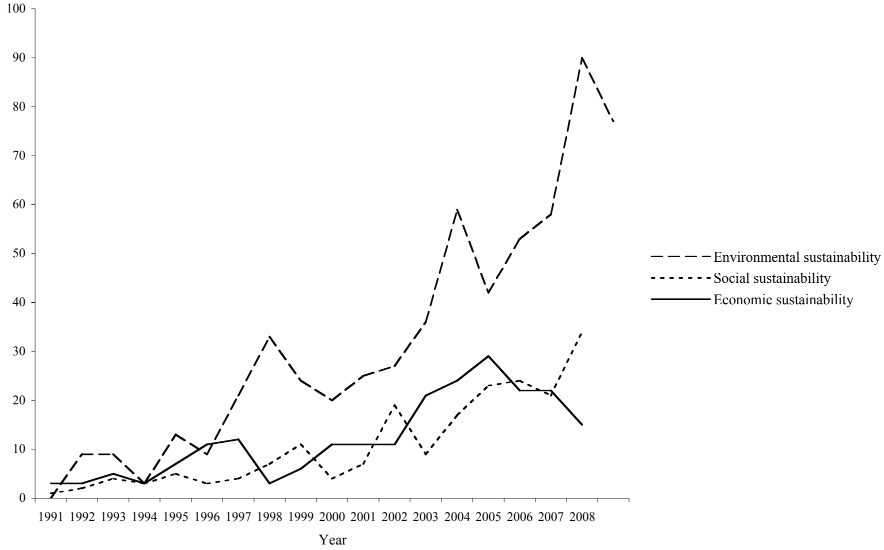

Figure 2 - Number of papers in the SCOPUS database published between 1991 and 2008 with the words 'environmental sustainability', 'social sustainability' and 'economic sustainability' in the title

It is perhaps unsurprising that environmental sustainability is the most developed of the three areas since much work on sustainability was born out of the green movement of the 1970s, and the idea that sustainability was multi-faceted in nature was not seriously considered until the mid 1990s. According to Sadler [7], sustainability assessment is often viewed as the next step on from single domain environmental assessment. While acknowledging the green roots of sustainability assessment, the weight of material on environmental sustainability provides a driver for making sure that the other aspects are given due consideration, even though they are less fully documented and less well understood.

2.5 Assessing sustainability

An assessment provides a framework for learning from experience so that better design is possible in the future [6]. A sustainability assessment therefore provides a means of reflecting on and measuring sustainable development [6]. Many methods have been proposed for assessing sustainability outcomes (usually at the project level), each with its own perspective and focus. Major methods include:

- **Strategic Environmental Assessment** (SEA) aims to incorporate environmental considerations into policies, programmes and projects at a high level. It is useful, since it considers impacts that go beyond the immediate local consequences of a project and looks at the bigger picture [17].

- **Environmental Impact Assessment** (EIA) involves assessing direct impacts of a project on the environment, considering alternatives and attempting to mitigate any deleterious effects [18].

- **Social Impact Assessment** (SIA) is largely similar to EIA in principle, although its application is less well advanced than that for EIA.

- **Multi Criteria Analysis** (MCA) offers an opportunity to assess multiple options in the face of varying stakeholder opinions. Its use has been championed in large scale public sector projects. It is through but is data intensive and requires weightings to be pre-assigned to various factors [19].

- **Life Cycle Assessment** (LCA) is a tool traditionally used in assessing environmental sustainability. It counters the problem of sustainability measures that only take into account one part of the product life cycle – for example pollution is often cleaned up at the end of an industrial process and clean up is a laudable activity, but there is a possibility that the clean up process leads to further problems (either upstream or downstream) [20]. LCA employs systemic thinking that addresses impact across the entire industrial life cycle of a product or process.

LCA is a standardised method and is defined by a series of ISO standards 14040 and 14044 [21]. These set out both the stages to be considered in the life cycle of the product, and the phases of the LCA method itself. This study uses an adapted LCA approach, in that it employs systemic thinking across each stage of a product life cycle, but it does not conform to the prescriptive method set out in the ISO standards since these apply to an environmental assessment rather than to all three major aspects of sustainability. This study does not aim to replicate an LCA as closely as possible nor force fit it to other aspects of sustainability, rather to employ the systemic principles that underpin it in providing a framework to evaluate sustainability in new product design.

2.6 Integrated approaches

It would be possible to analyse sustainability using separate assessments for each of the three pillars, without any form of methodological integration. The World Bank, in fact advocates this approach [9], although this perhaps reflects the global outlook that it takes. At the business level where there are immediate conflicts to be resolved and synergies to explore, integration of the themes is required in order to identify, assess and attempt to resolve trade-offs between them. In an ideal world, this would result in complete resolution whereby a win-win scenario is arrived at [22]. There is some potential to tread the middle ground in assessing the different aspects of sustainability separately and then bringing them together in an overall analysis, but this does not allow for the exploration of the interdependencies of the themes. This paper will thus present an integrated approach to assessing sustainability during the design phase of new products, using life cycle thinking as described above.

3 FRAMEWORK BUILDING

This work aims to collect from the literature environmental, social and economic sustainability considerations in new product design and group them so that they can be analysed using life cycle thinking. The collection of concerns is presented in a way that can be used in empirical work with businesses, in identifying (and describing) aspects of sustainability and life cycle phases that they consider to be important when designing new products. This representation is the framework, and the results of its use will feed the construction of a tool that analyses business capabilities in sustainable product design. Thus the ultimate goal is to improve sustainability outcomes in product design, with this study representing the preliminary steps towards assessing the capabilities needed to achieve this.

As alluded to above, a life cycle approach is used for the framework. Betz [23] describes the product life cycle as the 'requirements for producing, maintaining, supplying and disposing of a product'. (The product life cycle in this sense is distinct from the traditional product life cycle, which describes phases of the development of profits and sales of a product from launch to retirement [24].) For the purposes of the framework, the life cycle was divided into the following phases:

- Manufacture
- Distribution
- Use
- Maintenance
- End-of-life

Prior to manufacture, design must take place, but this has been separated from the rest of the list because the work aims to establish how the various stages in the list are planned for *during the design phase*. This is intended to highlight the importance of activity at the design stage of NPD, and the potential consequences of decisions taken during this phase.

Individual sustainability considerations from the literature were grouped according to which of the three pillars of sustainability they pertained to. Considerations were not restricted to one type of sustainability if they applied in more than one area. Following this, individual points were then plotted against phases of the product life cycle listed above to form the framework.

It was evident that when the collection of sustainability concerns from the literature are plotted on the framework, that they represented a wide selection of criteria: some were very specific, e.g. weight considerations in the supply chain, others were very broad: e.g. impact of the manufacturing process on local populations. Consultations with academic experts in the fields of sustainability, materials engineering and NPD concluded that the wide range of criteria needed to be accounted for, and seen from a design point of view. This was relatively straightforward for environmental concerns, however, for social and economic concerns, the criteria have remained fairly broad. With this in mind a second iteration of the framework was drawn up which aimed to fit the concerns to design strategies. This is shown in figure 3.

	Manufacture	Distribution	Use	Maintenance	End-of-Life
Social	•Socially responsible sourcing of labour [25] •Worker safety [26] •Worker health/quality of life [26] •Impact of manufacture on local population [27]	•Patent issues [32] •Access to design [25] •Socially responsible sourcing of labour [26] •Differential pricing [32]	•Inclusive design [37] [38] •User safety [32] •User dependence [32]	•Ease of repair [32] [40]	•Local impact of disposal [32][45]
Economic	•Component choice [26] •Material choice [26] [28] •Outsourcing choices [26] •Strategic product-service combinations [29]	•Logistics [25] [34] •Supply chain efficiency [1] [35] •Place of origin/outsourcing [26]	•Reliability [39]	•Cost to repair [29] [41] •Planned obsolescence [29] [43] •Lifespan [43][44]	•Financial impact of disposal [46]
Environmental	•Component choice [29][30] •Material choice [26][28] •Energy efficiency of manufacture [1] [31] •Avoidance of contamination [25]	•Energy efficient distribution [1] [34] • Weight considerations [36] • Transport packaging [1] [30] •Pollution minimisation [30] •Minimum use of hazardous substances [30]	•Energy efficiency [30], [1] [40] •Materials consumption [29] [30 •Avoidance of waste [1], [30] •Pollution minimisation [30] •Minimum use of hazardous substances [30]	•Durability [43] [44] •Ease of repair [29][40]	•Reuse / recovery of materials [1], [29], [30] [36] •Remanufacture [1] [43] [47] •Recycle [1] [48] •Disassembly [1], [30] [48] •Disposal (landfill or other) [45] [49] •Avoidance of contamination [25]

Figure 3 – Framework

4 DISCUSSION

4.1 Challenges in framework building

In conducting the literature review and building the subsequent model, the idea that the entire issue is highly complex and interrelated was reinforced. Sustainability concerns from literature yielded everything from sweeping generalisations to highly specific environmental concerns for the production of a particular item in a particular place. These concerns fell into four categories:

- Issues (e.g. Repair)
- Capabilities / Strategies (e.g. Design for Repair)
- Product characteristics (e.g. Ability to repair easily)
- Indicators / Measurables (e.g. Time to repair, number of spare parts needed etc.)

In terms of model building, the aim is ultimately to identify capabilities necessary during the design process in order to address sustainability holistically. In practice, this can be relatively straightforward for environmental concerns, but leaves something less structured for social and economic concerns. This is likely to be a consequence of LCA's origins as an environmental assessment tool.

A framework such as the one outlined in the study will never be absolutely comprehensive, despite best efforts to include all the relevant issues. Each business faces different challenges and issues, and each deals with them in slightly different ways. As such, it is likely that there are additions to the framework, which may be either general, or highly specific to a particular company. The latter is more likely, but will only become apparent during empirical work.

4.2 Balancing the sustainability portfolio – considerations at the business level

The model outlined in this study works at the product level; highlighting sustainability considerations for a single new product in the design phase. There is a possibility that, in a company with many products, optimising sustainability outcomes for one product could adversely affect those for another. For example, deciding to use a choose a different material for a product, rather than one used in several other products that the company makes could drive up the unit cost of production (both financially and environmentally) of the second product. This scenario illustrates the need to keep the model in context: tools that aid in the design process can offer input, but there is no substitute for the

judgment of the designer. A company with a range of products has to balance an entire portfolio of products rather than to wring every last drop of sustainability from one new product.
In addition the model does not deal with aspects of sustainability that are outside of the NPD process but which may be an integral part of business function. For example, most businesses over a certain size will have dedicated Human Relations and IT groups, each of which may (or may not) have its own sustainability considerations, and contribute indirectly to the sustainability of the company's products. This type of limitation harks back to the discussion on the boundaries of systems in the introduction, but the model is forward-looking and aims to assist designers in optimising the areas of new product design over which they have control – the new product.

4.3 The role of economic sustainability

In practice, economic sustainability for business does not have exactly the same goals as economic sustainability on a global level – a business needs to generate positive cash flow in the short to medium term as well as growth and profitability in the long term. To this end, the business must make decisions that are financially viable. For this reason, economic considerations are often one half of the tradeoffs identified in the design process. There may be a highly environmentally friendly material that could be used in making a new product that is prohibitively expensive.
The familiar tradeoff of cost *versus* social/environmental sustainability considerations begs the question of whether it can be worth raising the production cost of a product to enhance its sustainability. A commonly cited argument for doing this is that customers would prefer to pay slightly more for a more sustainable (this usually means 'greener', but social examples (such as Fair Trade products) exist) item, but there is little evidence that this actually happens [2]. In other words, products must still be economically competitive to be viable – increased sustainability alone is not enough. This does not necessarily mean that the product must be as cheap as it possibly can be, but rather that careful attention must be paid to the resolution of these particular conflicts.

4.4 Environmental – social conflicts

Not all sustainability decisions involve trading off cost with other considerations. Environmentally sustainable solutions are not always in synergy with socially sustainable solutions. For example, a product which has been designed according to inclusive design principles may incorporate a light to aid partially sighted, or hearing impaired users, but design for environment principles dictate that there should be no unnecessary use of energy (to light the light bulb). The resolution for this type of tradeoff depends both on the remit for the design of the product, and the marginal cost (social or environmental) associated with implementing, or not implementing, the change.

4.5 Identifying synergy

TBL approaches have been criticised (for example by Pope *et. al.* (2004) [8]) for failure to give adequate coverage to synergistic solutions. The framework permits the identification of synergies (for example where a more environmentally sustainable material is actually more cost effective) sustainability as well as the identification of conflict. In the construction of the model, conflicts were found to be much more generic than synergies. In other words, synergy generally only becomes apparent on a case-by-case basis.

4.6 Implications for designers

Where a potential conflict is identified, the designer must recognise and solve the tradeoff as part of the design process. In addition to conflicting sustainability demands, there may be other constraints such as laws, limited time to gather data or firm policy that dictates, for example, that certain suppliers must be used. In an ideal situation, the examination of sustainability conflicts would lead to the implementation of a 'win-win-win' solution, where all three sustainability goals are satisfied. In practice, this rarely happens, and the designer's job is then to design towards this as far as possible.
As the model is applied to specific design scenarios, it is likely to flex. What is important in the design of one product may be almost inconsequential in the design of another. It is impossible to assign these weightings outside of the design process itself; the decision to prioritise one set of issues over another rests with the designer.

5 FUTURE WORK

In the medium term, the framework developed in this study will be used to form the basis of case studies with manufacturing businesses. These case studies will aim to determine which areas of sustainability, and phases of the product life cycle businesses deem to be important, and what action they take in designing for these concerns. The interaction with industry is designed to address two major research questions:

1. To what extent are sustainability issues in new product design being considered in firms?
2. What are the capabilities needed to develop sustainable new products, and how might such capabilities be assessed?

Investigation of these issues will contribute to the construction and refinement of a tool for analysing business capabilities in sustainable product design. In the long term, it is hoped that, despite the complexity of the issues involved, awareness and development of appropriate capabilities will improve best practice and contribute towards sustainable product portfolios in industry.

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REFERENCES

[1] Choi J.K., Nies L.F. and Ramani K. A framework for the integration of environmental and business aspects toward sustainable product development. *Journal of Engineering Design,* 2008, 19(5), 431-446.
[2] Ambec S. and Lanoie P. Does it pay to be green? A systematic overview. *The Academy of Management Perspectives,* 2008, 22(4), 45-62.
[3] Ulrich K.T. and Eppinger S.D. *Product Design and Development*, 2003 (McGraw-Hill/Irwin, New York).
[4] World Commission on Environment and Development. Our Common Future, 1987 (Oxford University Press, Oxford).
[5] Elkington J. Towards the sustainable corporation: Win-win-win business strategies for sustainable development. *California Management Review,* 2004, 36(2), 90-100.
[6] Guijt I. and Moiseev A. IUCN Resource Kit for Sustainability Assessment, 2001 (IUCN, Gland).
[7] Sadler B. A framework for environmental sustainability assessment and assurance. In: Petts J. (ed) Handbook of environmental impact assessment, Volume 1, 1999 (Blackwell, Oxford).
[8] Pope J., Annandale D. and Morrison-Saunders A. Conceptualising sustainability assessment. *Environmental Impact Assessment Review*, 2004, 24, 595-616.
[9] Daly H.E. and Cobb J.B. For the Common Good, 1989 (Beacon Press, Boston).
[10] Goodland R. Sustainability: Human, Social, Economic and Environmental. Encyclopedia of Global Environmental Change, 2002 (John Wiley & Sons / World Bank, New York)
[11] Vink E.T.H., Rabago K.R., Glassner D.A. and Gruber P.R. Applications of life cycle assessment to NatureWorks polylactide (PLA) production. *Polymer Degradation and Stability,* 2003, 80, 403-419.
[12] Goodland R. The concept of environmental sustainability. *Annual Review of Ecology and Systematics,* 1995, 26, 1-24.
[13] Doane D. and MacGillivray A. Economic Sustainability: The business of staying in business, 2001 (New Economics Foundation, London).
[14] Lehtonen M. The environmental-social interface of sustainable development: capabilities, social capital, institutions. *Ecological Economics,* 2004, 49, 199-214.
[15] Waage S.A., Geiser K., Irwin F., Weissman A.B., Bertolucci M.D., Fisk P., Basile G., Cowan S., Cauley H. and McPherson A. Fitting together the building blocks for sustainability: a revised model for integrating ecological, social and financial factors into business decision-making. *Journal of Cleaner Production,* 2005, 13, 1145-1163.

[16] Maxwell D., Sheate W. and van der Vorst R. Sustainable Innovation in Product and Service Development. In *Towards Sustainable Product Design 8,* Stockholm, October 2003.
[17] http://www.sea-info.net/, retrieved January 2009.
[18] Senecal P., Goldsmith B., Conover S., Sadler B. and Brown K. Principles of Environmental Assessment Best Practice, 1999 (International Associated for Impact Assessment, Fargo).
[19] http://www.cifor.cgiar.org/acm/methods/mca.html, retrieved January 2009.
[20] Azapagic A. Life Cycle Thinking and Life Cycle Assessment (LCA). In: Azapagic A. Perdan S. and Clift R. (eds) Sustainable Development in Practice Case Studies for Engineers and Scientists, 2004 (John Wiley & Sons, Chichester).
[21] ISO 14040 and ISO 14044 Environmental Management series, 2006 (ISO, Geneva).
[22] Hacking T. and Guthrie P. A framework for clarifying the meaning of Triple Bottom Line, Integrated and Sustainability Assessment. *Environmental Impact Assessment Review,* 2008, 28, 73-89.
[23] Betz F. Managing Technological Innovation: Competitive advantage from change, 2003 (John Wiley & Sons, New York).
[24] Kotler P., Armstrong G., Wong V. and Saunders J. Principles of Marketing (5th Edition), 2005 (Finanial Times / Prentice Hall).
[25] Seuring S. and Muller M. From a Literature Review to a Conceptual Framework for Sustainable Supply Chain Management. *Journal of Cleaner Production*, 2008, 16, 1699-1710.
[26] Hutchins M. and Sutherland J. An exploration of measures of social sustainability and their application to supply chain decisions. *Journal of Cleaner Production*, 2008, 16, 1688-1698.
[27] Ma J., Cheng J., Xie H., Hu X., Li W., Zhang J., Yuan T. and Wang W. Seasonal and spatial character of PCBs in a chemical industrial zone of Shanghai, China. *Environmental Geochemistry and Health*, 2007, 29, 503-511.
[28] Gamage G., Boyle C., McLaren S.J., and McLaren J. (2008). Life cycle assessment of commercial furniture: A case study of Formway LIFE chair. *International Journal of Life Cycle Assessment,* 2008*,* 13, 401-411.
[29] Kang M-J. and Wimmer R. Product service systems as systemic cures for obese consumption and production. *Journal of Cleaner Production*, 2008, 16, 1146-1152.
[30] Knight P. and Jenkins J.O. Adopting and applying eco-design techniques: a practitioners perspective. *Journal of Cleaner Production*, 2009, 17, 549-558.
[31] Hara M. Environmentally benign production of biodiesel using heterogeneous catalysts. *ChemSusChem*, 2009, 2, 129-135.
[32] Whiteley N. Design for Society, 2003 (CPI/Bath Press, Bath).
[33] http://laptop.org/en/, retrieved January 2009.
[34] Haven J. Driving a sustainable supply chain. *Environment Business*, 2007, 135, 22-23.
[35] Ji G. Closed-loop supply chains based on by-product exchange. Proceedings of *2008 IEEE International Conference on Service Operations and Logistics, and Informatics,* IEEE/SOLI 2008 2, art. no. 4682939, 2405-2410.
[36] Lofthouse V.A. Creative Idea Generation for Refillable Body Wash Products. 2007 In *International Conference on Engineering Design, ICED'07,* Paris, August 2007.
[37] Clarkson J., Coleman R., Hosking I. and Waller S. Inclusive Design Toolkit, 2007 (Engineering Design Centre, Cambridge)
[38] Heylighen A. Sustainable and inclusive design: A matter of knowledge? *Local Environment*, 2008, 13, 531-540.
[39] Seager T.P. The sustainability spectrum and the sciences of sustainability. *Business Strategy and the Environment*, 2008, 17, 44-453.
[40] Martínez E., Sanz F., Pellegrini S., Jiménez E. and Blanco, J. Life cycle assessment of a multi-megawatt wind turbine. *Renewable Energy*, 2009, 34, 667-673.
[41] Zhou X., Yang J., Wang F. and Xiao, B. Economic analysis of power generation from floating solar chimney power plant. *Renewable and Sustainable Energy Reviews*, 2009, 13, 736-749.
[42] Sun W. and Sun P. (2008). Post Planned Obsolescence. *9th International Conference on Computer-Aided Industrial Design and Conceptual Design: Multicultural Creation and Design* - CAIDCD 2008, art. no. 4730732, 1009-1011.
[43] Mont O. Innovative approaches to optimising design and use of durable consumer goods. *International Journal of Product Development*, 2008, 6, 227-250.

[44] Goering G.E. Socially concerned firms and the provision of durable goods. *Economic Modelling*, 2008, 35, 575-583.
[45] Bian Z., Dong J., Lei S., Leng H., Mu S. and, Wang H. The impact of disposal and treatment of coal mining wastes on environment and farmland. Environmental Geology*,* 2008, published online.
[46] Swainston J., Wright S. and Bruckard, W. Opportunities for used consumer battery recycling in the Australia/Pacific region. *Australasian Institute of Mining and Metallurgy Publication Series*, 2006, 55-59.
[47] Charter, M. and Gray C. Remanufacturing and product design. International Journal of Product Development, 2008, 6, 375-392.
[48] Jekel L.J. and Tam E.K.L. Plastics waste processing: Comminution size distribution and prediction. *Journal of Environmental Engineering*, 2007, 133, 245-254.
[49] Heijungs R. (ed) (1992). Environmental Life Cycle Assessment, (Multicopy, Leiden).

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