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ECO-INNOVATION: THE OPPORTUNITIES FOR ENGINEERING DESIGN RESEARCH

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1. Introduction

Environmental sustainability challenges, plus the increasing range of environmental pressures faced by industry, means that there is an urgent need for approaches that can deliver step change improvements in the environmental performance of products. Eco-innovation is an approach that has the potential to meet this need. However, despite continuous and on-going research in this area stretching back nearly 20 years, it is still a relatively low level of maturity, particularly if we use the uptake by industry as the measure of maturity [McAloone et al. 2002], [O'Hare 2010]. An additional concern is that the inherently inter-disciplinary nature of eco-innovation means that there is a higher risk of the ending up with a fragmented research domain, leading to poor support for practitioners.

The engineering design research community is in a position to make a significant contribution to the advancement of the theory and practice of eco-innovation as the development of products lies at the core of the eco-innovation concept. To capitalise on this potential, it is important to have an understanding of the existing body of knowledge and the future research opportunities. The aim of this paper is therefore to provide a review and reflection of on the current status of eco-innovation research and suggest areas where the design community can contribute to developing the maturity of this approach. This is done through a selective review of the academic literature, choosing examples of research that give a flavour of some of the key trends and interesting topics that are emerging from the eco-innovation body of knowledge, as well as providing some indication of the breadth of topics being investigated. In the conclusions we suggest 10 areas where we see potential for the engineering design research community to contribute to the advancement of eco-innovation.

2. Approach

Although this review was not intended as a systematic review, certain methodological steps were taken to increase the range of papers discovered and analysed. First, a definition of eco-innovation was selected. A variety of authors, organisations and expert panels have provided definitions of eco-innovation [O'Hare 2010]. For the purpose of this literature review, we adopt the definition by provided by James [1997], based on the work by Fussler and James [1996], who states that, "Eco-innovation aims to develop new products and processes which provide customer and business value but significantly decrease environmental impact."

This definition was chosen for its simplicity and the fact that the work by Fussler and James is still being regularly cited over 15 years later, which would suggest it has some merit. It is understood by the current authors that the significant decrease in environmental impact mentioned in this definition is assessed over the full lifecycle of the product or process – a point which is not explicit in this definition but is the clear intention of James.

Secondly, a simple conceptual model was devised. This was taken from the definition of eco-innovation, which suggests three domains of academic research that can most directly and logically make a contribution to eco-innovation theory and practice:

- '…develop new products and processes…' = engineering design
- '…which provide customer and business value…'= strategy and management
- '…but significantly decrease environmental impact'=environmental science

These three domains where therefore chosen to limit the scope of the literature review. This conceptual model is captured in Figure 1, with the addition of the some of the specific topics discussed in the review.

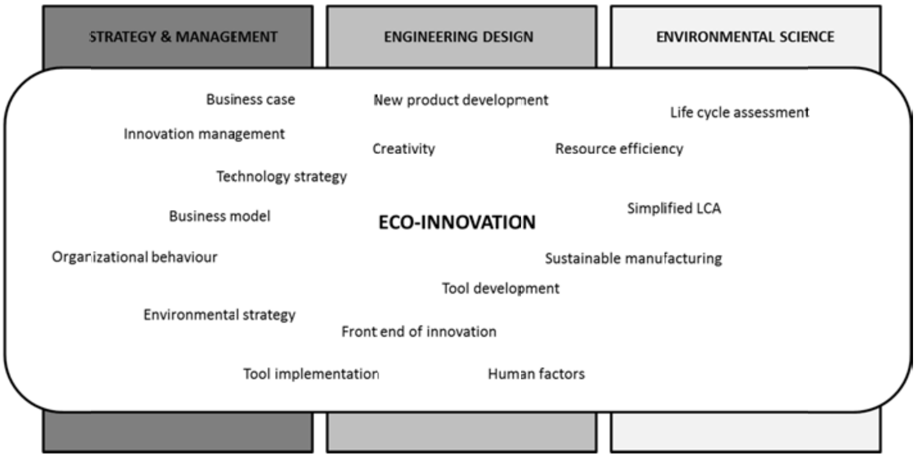

Figure 1. The conceptual model used to inform the search for relevant literature

Whilst there may be other domains that contribute to the development of eco-innovation that are not represented in this model, these are of less concern for the current review as the aim is to identify opportunities for the engineering design community and so the focus is on the contributions from within the engineering design domain and from the domains that (conceptually) border this domain. The review therefore focuses on three main areas: the contribution to eco-innovation from the engineering design perspective; the contributions from the interface with strategy and management; and the contributions from the interface with the environmental science perspective.

In terms of additional limitations of scope, the following decisions were made. No limit was placed on the timescales of the literature searched. Articles focused on social aspects of sustainability were discounted as the focus was on environmental aspects of sustainability. Articles focused on applications of eco-innovation in areas such as architecture and chemical engineering were discounted as the focus was on engineering design of products.

A variety of sources were searched including ScienceDirect, the Journal of Cleaner Production and Google Scholar. The snowball method was also used to identify additional articles. The choice of articles to include in the review was primarily based on the authors experience and knowledge of the domain but was also influenced by the number of citations received by an article, as an indication of the importance of the contribution.

3. Review findings

The review findings are presented over the following three sub-sections. First we consider the contributions on eco-innovation within the engineering design literature. Secondly, we look at the interface with the domain of strategy and management. Finally, we consider the contributions from the interface with environmental science.

3.1 Engineering design literature on eco-innovation

One of the contributions of the engineering design domain to eco-innovation has been the development of tools for eco-innovation. Examples of these tools include:

- Lifecycle Design Strategies (LiDS) Wheel [Brezet and van Hemel 1995] and the similar Eco-compass [Fussler and James 1996], which both support the evaluation of new concepts through the use of a semi-quantitative, comparative assessment of the environmental properties of the new concept against the existing product.
- Product Ideas Tree diagram [Jones 2003], which supports the generation of eco-innovative concepts by providing a structured approach to capturing ideas from idea generation sessions.
- Eco-Design Tool [Chang and Chen 2004], which adapts the TRIZ contradictions matrix and inventive principles to help support eco-innovative idea generation and problem solving.
- 'Eco-ideation tool' [Bocken et al. 2011], which supports eco-innovative idea generation by using a set of prompting questions and associated indicators that provide a quick and approximate prediction of the product or process parameters that are likely to contribute most to the overall greenhouse gas emissions of the product.

It is noteworthy that relatively few examples of tools that explicitly support eco-innovation were identified – a finding which is consistent with previous reviews [Gomez-Navarro 2005], [O'Hare 2010]. For comparison, a comprehensive literature review by Baumann et al. [2002] identified over 150 tools that were relevant to the broader field of 'Environmental Product Development' – which includes eco-design as well as eco-innovation. There are a number of possible explanations for the dearth of eco-innovation tools identified, relative to the abundance of eco-design tools. It may be that methodological flaws in the literature search procedure have resulted in a large number of tools being missed. Alternatively, it could be that tools that are relevant for eco-innovation are not being explicitly labelled as such because: that is not there primary focus; the keyword 'eco-innovation' was not used in the paper in which they are described; or because the developers of the tool are themselves not aware of the potential of their tool for use in eco-innovation. Whatever the explanation, a more comprehensive and rigorous review, with clear criteria for what constitutes a 'relevant' tool for eco-innovation, could unearth a significant number of 'new' eco-innovation tools from the existing literature.

Of the eco-innovation tools that do exist, what has been the uptake by industry? Disappointingly poor is the conclusion from most authors [Jones 2003], [Petala et al. 2010], [O'Hare 2010]. The same problem has been noted for eco-design tools and a number of possible causes for this poor uptake by industry have been offered, including [summarised from O'Hare 2010]:

- No systematic introduction process – Tools are often introduced within a company without any formal analysis of the need that the tool is intended to fulfil, with choices about the type of tool and how and when it should be introduced often done on an ad-hoc basis.
- Tool not customised to the specific application – There are many variations in product development activities between companies related to organisational, cultural, process and product differences. These differences may require the tool to be customised to the specific application but this is not normally considered.
- No demand – If there are no environmental criteria in the product requirements specification then quite simply there is no need for eco-innovation tools.
- No time - Environmental impacts are just one of many constraints a designer must consider during product development and hence only a very limited amount of time and effort can be spent on them.
- Designers' requirements not considered – Tool developers have lacked a thorough understanding of how designers use tools and their main considerations when choosing whether or not to use a tool.
- 'Human factors' not considered – when a new working practice is introduced into an organisation, including the use of eco-innovation tools, there is always a risk that the change will face resistance, at an organisational or individual level.

Some of these issues have been addressed within the core engineering design literature. For instance, Lofthouse [2006] has provided greater insight into designers' requirements of tools for eco-design. Other issues, such as the consideration of human factors, stray into the interface regions and will require input from other domains to address successfully. A summary of the approaches recommended in the design literature to increase the adoption of eco-innovation is provided by O'Hare [2010]:

- Decrease the level of effort required to apply the tool or the complexity of the tool.
- Gain a better understanding of the user's requirements.
- Ensure that environmental considerations are integrated within the New Product Development (NPD) process.
- Select tools that fit within the NPD process and fit the task.
- Ensure that the tool is aligned with the strategic goals of the organization.
- Improve the tool training programme.
- Use a systematic tool introduction process.
- Customise the tools to the specific company or application.

Tool customisation was the most commonly recommended approach and was subsequently found by O'Hare to be a successful strategy when applied within six case study companies. However, further work is necessary to evaluate the other strategies proposed for increasing eco-innovation tool uptake.

Another contribution from the engineering design domain has come from Jones [2003], who has provided a recommended process for eco-innovation, Figure 2. The process emphasises the importance of early-stage workshops aimed at generating a large quantity of radical ideas.

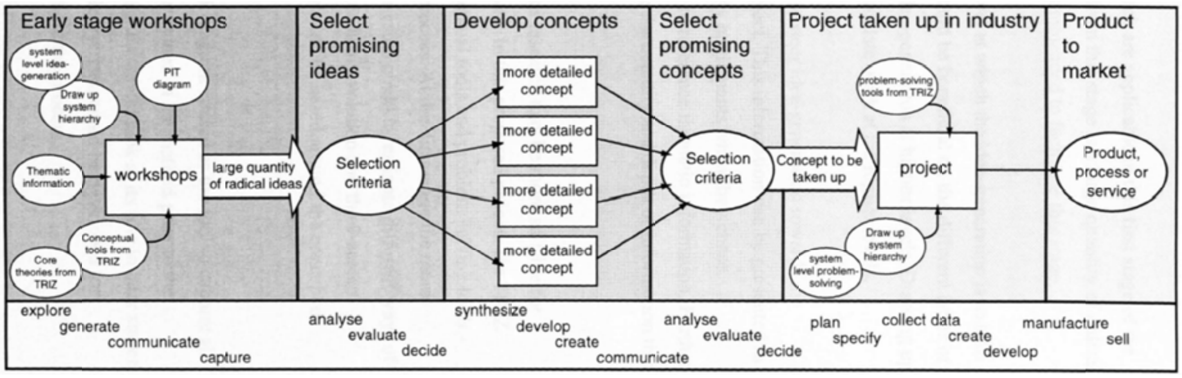

Figure 2. Recommended process for eco-innovation [Jones 2003]

A consistent theme from the engineering design perspective of eco-innovation has been the importance of the early stages of the innovation process. This would appear to stem from the widely held view that the early stages dictate, or 'lock-in', the vast majority (~80%) of a product's lifecycle environmental impacts (although, as Bauman [2002] notes, there appears to be little empirical evidence directly supporting this view). This has led to a number of pieces of research that have focused on the early stages of innovation, including:

- Jones [2003] investigated ways of supporting early-stage ideation workshops and proposed a number of tools to help stimulate idea generation and facilitate the efficient capture and recording of ideas.
- Olundh [2006] looked at how companies can incorporate environmental considerations into the early stages and concluded the setting environmental targets and assessing the potential for environmental gains play an important role in ensuring this occurs.
- Petala et al. [2010] concluded from a study of 202 NPD briefs at Unilever that simply having sustainability criteria listed on NPD brief templates was not enough to ensure that sustainability was given due consideration during the design activity.
- Bocken et al. [2014] conducted a survey (n=42) of SMEs engaged in eco-innovation in The Netherlands to investigate their early stage eco-innovation activities, including the types of tools and frameworks they use to support eco-innovation. Informal tools such as 'brainstorming' and 'pen and pencil' were found to be the most commonly used tools whilst Life Cycle Assessment, Cleaner Production and Cradle to Cradle were all found to be employed to a greater or lesser extent.

In summary, the contributions of the engineering design research community to eco-innovation includes: the development of tools; best-practice advice to support the implementation of those tools; advice on the process for eco-innovation development activities and a variety of contributions related to the front end activities. In the following section we review the contributions to eco-innovation emerging from the interface with the domain of strategy and management.

3.2 Interface with strategy and management

One of the key contributions to eco-innovation from the management literature has been an understanding of the business case for pursuing improvements in sustainability performance (using approaches such as eco-innovation). A comprehensive review of this domain is provided by Schaltegger et al. [2011], who identify the following areas in which companies may find business benefits according to the literature: cost reduction; sales and profit margin; risk and risk reduction; reputation and brand value; attractiveness as employer; innovative capabilities.

The authors go on to state that a business case for sustainability should show the following characteristics:

- Involves a voluntary activity (not entirely driven by regulatory compliance) with the intention to contribute to the solution of societal or environmental problems.
- The activity must create a positive business effect or a positive economic contribution to corporate success which can be measured or argued for in a convincing way.
- A clear and convincing argumentation must exist that a certain management activity has led or will lead to both, the intended societal or environmental effects, and the economic effect.

This definition places an emphasis on the pro-active and planned pursuit of environmental benefits, rather than on the serendipitous environmental and business benefits that may occur from business as usual. In line with this thinking, the authors stress the need for companies to adapt their corporate environmental strategy and show innovation in their business model if they wish to realise greater business benefits from pursuing environmental goals. They propose an integrated framework, linking sustainability strategy, business case drivers, and business model innovation. In short, a company that aims to adopt the most progressive and ambitious level of sustainability strategy will realise the strongest business case for sustainability, but it will generally require a complete business model redesign to achieve the business benefits. The business model innovation is required to ensure that opportunities for improved sustainability performance (and business benefit) are identified and exploited throughout the business, including the value proposition, the relationship with the customer, the business infrastructure and the financial management of the company.

The need for such radical changes to the strategy and business model raises the question of whether it is easier for start-up companies or small companies to become eco-innovators than it is for larger companies, which may have greater 'inertia' and resistance to innovation than their small counterparts. This has led to increased interest in the role of small companies in leading a new green industrial revolution. For instance, Larson [2000] analyses a longitudinal case study of an eco-innovative start-up company through an entrepreneurship lens. The case study evidence reinforced many of the issues that had previously been highlighted as important in explaining cases of successful entrepreneurship activities. These include:

- The coming together of a market opportunity and an individual with the right set of skills and competencies to exploit the opportunity.
- The value of having a strong sustainability vision for the company or sector from the outset.
- The need to view the entire value chain as a potential source of innovation.
- The need to mobilize a network of actors to bring together the necessary skills and resources.

Others have chosen to focus on how existing, large companies can transition to more eco-innovative approaches and business models. Tan et al. [2007] have reported on a participatory action research project within a leading office furniture manufacturer that had a stated aim to generate more revenue from services whilst simultaneously improving its environmental performance by adopting a Product/Service System (PSS) business model. The lead researcher spent three months working alongside the product development team and was able to identify a number of challenges that the company faced in the early stages of its transition to the PSS approach, including:

- to consider what has to be done to reach the (new) intended target clients of the PSS offering, while still satisfying the usual stakeholders,

- to determine whether the suggested PSS approach can co-exist with the established operational organisation (or does it needs to be developed in a separate organisation?),
- to form partnerships and create a new unique value network that collaboratively can provide the total customer offering,
- to establish a development approach for the concurrent consideration of context, content and delivery channel,
- to establish an information infrastructure that can manage both product data, as well as information of the user and use activities,
- to design value-added activities and engaging interactions with the customer,
- and to create structures and incentives that encourage sustainable behaviour amongst users.

Most, if not all, of these challenges have significant implications for how the products and services offered by the company are developed and are therefore highly relevant for the engineering design community.

Moving beyond the level of strategy and business model, there have also been contributions that aim to support the operational level management of eco-innovation activities. Based on a review of the literature, Pujari [2006] identified a number of management characteristics that were considered important in determining eco-innovation success. A survey of North American product managers (n=68) covering a variety of industries was completed to assess their views of the importance of the management characteristics identified from the literature. The subsequent statistical analysis revealed some surprising results. For example, the proposition that a higher degree of upfront feasibility-related activities positively influences the eco-innovation performance was not validated. This is contrary to the widely held view that the early stages of innovation are critical to eco-innovation success. Factors that were found to have a positive effect on eco-innovation performance include higher degrees of: cross-functional coordination; supplier involvement; market focus; and LCA activity undertaken.

The finding that a higher degree of cross-functional coordination is correlated with better eco-innovation performance reinforces the proposal from Millet et al. [2007] for environmental experts to play a more central and integrated role within the product development team. However, the finding that a higher degree of LCA activity undertaken (including the availability of environmental data and tools for the design team) is linked to better eco-innovation performance appears to conflict with the recommendations of Millet et al. [Ibid]. Nevertheless, this research provides an important contribution by attempting to quantitatively assess and challenge some of the widely held views that have often been stated in the engineering design literature.

Further surprising empirically-derived insights come from Cheng et al. [2013], who performed a survey of Taiwanese manufactures (n=121) to investigate the relative influence of products, production processes and organizational eco-innovations on company performance. They found that organizational eco-innovations have the greatest influence on business performance, followed by eco-production process innovations and then eco-product innovations. This leads them to conclude that companies implementing eco-innovation should focus on organizational aspects first (training, knowledge, infrastructure), which will create necessary conditions for process innovation, which in turn can support the development of product eco-innovations. This would appear to reinforce the call by Boks [2006] for greater research on organizational factors in eco-innovation.

Based on recommendations from radical innovation management literature and case-study insights from successful eco-innovators, O'Hare [2010] has described a model of eco-innovation management. The model suggests that the internal demand for eco-innovation must be driven from the strategic level, from where ambitious environmental goals cascade down through the organisation and finally appear as concrete requirements within the requirements specification. The model also emphasises the need to manage eco-innovation development activities as 'pre-development' or 'Research & Development' projects, as the NPD process, used to manage conventional, incremental improvement projects, is not suitable for the long time-scales, high risk and uncertain nature of eco-innovation. This model also helps to highlight the additional scope and complexity of managing eco-innovation in comparison with eco-design activities. These important differences between eco-design and eco-innovation may limit the transferability of insights between these two topics.

3.3 Interface with environmental science

At the boundary of engineering design and environmental science an important contribution is made in understanding the environmental impacts of product and systems. Life Cycle Assessment (LCA) is the framework that has been developed to support the assessment of a products environmental performance. One of the key challenges for eco-innovation has been the time-consuming and costly nature of performing a detailed LCA study, which is often incompatible with the short lead times and tight budgets of NPD activities. This has led to research in the area of Simplified Life Cycle Assessment (SLCA) tools.

Hochschorner and Finnveden [2003] have assessed the relative merits of two semi-qualitative SLCA methods – the Environmentally Responsible Product Assessment (ERPA)-Matrix, and MECO-method (MECO:Materials, Energy, Chemicals, Other). They applied both methods to the same case study product and compared the results with the results from a detailed, quantitative LCA. They found that the MECO-Matrix provided some additional insights into the environmental performance of the product that complemented the information gained from the quantitative LCA. The ERPA-Matrix was found to be less useful, mainly because it does not cover the full lifecycle of the product. They conclude that the use of simplified, semi-qualitative LCA methods such as the MECO-Method may be useful both as an early-stage precursor to a quantitative LCA and as a supplementary source of information, providing new insights that can inform the interpretation activity.

Hur et al. [2005] performed a similar study but focused on simplified, quantitative methods, rather than semi-qualitative methods. Starting from a conventional LCA method, 11 simplified SLCA methods were generated by progressively reducing the lifecycle scope of the method and the amount of primary data used (substituted with secondary data). Comparing the results of these methods to a 'complete', quantitative LCA method, it was found that five of the methods delivered 90% accurate results (exclusion of the use phase significantly reduced the accuracy of the remaining methods). Evaluating the relative effort of each of the methods, they found that two methods were able to offer significant reductions in the time and effort to perform the assessment whilst still retaining very high accuracy in comparison to the conventional LCA method. It was concluded that SLCA can make a useful contribution to eco-innovation development activities by providing a neutral assessment of the environmental performance of a new concept. An additional noteworthy point raised by the authors is that, because SLCA is based on the concept of a 'functional unit', it is possible to compare significantly different technologies, products and systems that fulfil the same function [Ibid]. Given that eco-innovation will often involve changes in technology and even systems-level change, this makes the concept of the functional unit an important one for practitioners engaging in eco-innovation to understand and utilize.

The case has therefore been made, from an environmental science perspective, for the value of SLCA methods in the development of eco-innovations. But does this potential translate into practical value from an engineering design perspective? Drawing on practical experience from industry collaborations, Millet et al. [2007] pick up this theme and ask if LCA is suitable for use by the design team during the NPD process. They conclude that its use in answering short term issues is limited because its primary strength is in the analysis of existing products or well defined products at the end of the design process. In the long term, LCA can be useful in identifying the typical environmental hotspots of a product, which can help the company to make environmental performance gains by informing R&D activities to address the key phases of the product lifecycle or problematic materials. However, they note that the use of LCA can have negative consequence for the eco-innovation performance of the company by:

- creating confusion amongst the design team due to the new and complex terminology;
- alienating the environmental expert from the rest of the design team;
- causing innovative concepts to be rejected because of the difficulty of assessing their environmental performance using the LCA method;
- encouraging a focus on details rather than the 'big picture', thereby leading to incremental improvements over radical, step-change innovations.

They therefore recommend that the use of LCA be limited to the assessment of new technologies and concepts at a strategic level (rather than a project level) where it can help to guide a company's technology roadmap, environmental policy and business strategy. In addition they suggest that LCA should be considered to be a specialised tool that is only for use by environmental experts.

Whilst the LCA community continue to pursue progress in the scientific robustness of the LCA framework, it seems there is now widespread recognition of the need to develop additional knowledge on how to encourage a wider practical application of LCA in the support of activities such as eco-innovation. As well as the development of the aforementioned simplified LCA approaches, there have been developments aimed at improving the accessibility, usability, integration and cost-effectiveness of LCA tools. One example comes from Buttol et al. [2011], who report on the development and application of web-based platform (www.ecosmes.net) that offers holistic support for eco-innovation in SMEs. Modules of the platform provide:

- Training material to raise awareness of environmental issues and regulatory drivers for eco-innovation.
- Simplified LCA to understand the environmental hotspots across the product lifecycle.
- A structured approach to (re)designing a product to minimize environmental impacts, based on the QFDE (Quality Function Deployment for the Environment) approach.
- Guidance and support services to help the company with product environmental performance communication issues e.g. eco-labelling and marketing issues.

The authors report on a variety of successful applications of the platform, leading to environmental performance improvements of up to 40%. They foresee the platform being used for publishing of LCA results and suggest that semantic web technology could be used to enhance the platform to support the cost-effective gathering and sharing of product lifecycle data.

In summary, the contributions to eco-innovation from the borders with environmental science innovation include: the development of LCA as a scientifically robust framework for understanding the environmental performance of products; the development of simplified LCA methods and tools that attempt to reduce the time and cost of performing and LCA study; and practical tools and platforms aimed at improving the accessibility, usability, integration and cost-effectiveness of LCA.

4. Conclusions

This paper has provided a selective review of the eco-innovation literature from within the engineering design domain and also from the across the bordering domains of management and strategy, and environmental science. By providing an initial attempt at mapping the territory of eco-innovation the aim was to identify the opportunities for the engineering design research community to contribute to the advancement of eco-innovation theory and practice. Based on the review findings, we present a summary of the opportunities identified.

1. **A widely accepted typology of approaches to environmental product design** – attempts at such a typology, incorporating eco-innovation, eco-design and other related approaches, have been made both within the engineering design [Brezet 1997] and from other domains. However, none of these have gained wide acceptance. The result is a confusing array of terminology and definitions. This makes it difficult to identify relevant literature and severely hinders cross domain collaboration and sharing of insights.
2. **A comprehensive and rigorous review of tools to support eco-innovation** – with clear criteria for what constitutes a 'relevant' tool and a systematic approach, such a review could unearth a significant number of 'new' eco-innovation tools from the existing literature.
3. **Guidance on when and where eco-innovation is relevant –** The literature suggests that the level of environmental ambition, skills, knowledge and resources required for eco-innovation mean that it is not suitable for all companies, or for all product development projects. Advice is therefore need on how to decide when and where it is relevant and feasible.
4. **Collaborative research at the interfaces** – the literature reviewed provided few examples of collaboration across the domains of engineering design, management and strategy, and environmental science. The existing examples of research taking place at the interface between these domains demonstrate that there are interesting topics in these regions, but this work was typically conducted by research teams composed entirely of researchers from one

domain. Inter-disciplinary projects could help to overcome some of the terminology issues highlighted above and promote more efficient exchange of ideas.

5. **Studies of eco-innovation implementation** – There is still very little information to guide companies on how they should go about implementing eco-innovation. Such studies are emerging from the eco-design literature [Pigosso et al. 2013], but due to the important differences in the nature of eco-design and eco-innovation, the transferability of findings may be limited. Therefore studies focused specifically on eco-innovation implementation are required.
6. **Greater reporting of case studies of failures** – the literature on eco-innovation implementation provides some best-practice case studies but does not provide information on cases of failure. With an increasing number of companies showing interest in adopting eco-innovation it seems likely that some companies have tried but failed to implement eco-innovation practices and tools. Reporting of such case studies is likely to be challenging but would provide interesting insights and lessons that other could benefit from.
7. **Methodological innovation** – the management literature has provided some interesting examples of methodological approaches to the study of eco-innovation that are not widely used in engineering design research. The longitudinal case study performed by Larsson [2000] provided rich and holistic insights into the process of starting-up an eco-innovative company. Similarly the methodological rigour applied in the survey-based studies by Cheng et al. [2013] and Pujari [2006] have yielded empirical data that challenges some of the widely-held, but untested, views to be found in the engineering design literature.
8. **Bringing design thinking to business model innovation** – The review highlighted the need for business model innovation as a key activity for companies seeking greater business benefits from pursuing improved environmental performance. The analytical and creative competencies required for business model innovation correlate well with the skill set of engineers, designers and the engineering design research community. Business model innovation is also a key topic in that it provides a bridge between the domains of business strategy and the technical domain of engineering design. It is therefore a good candidate topic for the collaborative research approach advocated above.
9. **Understanding the role of LCA in supporting eco-innovative product development –** the environmental science research community have developed a variety of simplified LCA approaches and more practical tools that are intended to help increase their adoption and value within engineering design activities. However, as the review has shown, there is still uncertainty concerning who, when and how such tools can be applied to greatest effect.
10. **Development of an interface with policy research** – a significant amount of literature on the topic of eco-innovation exists within the policy research domain, but as yet, the linkages with the engineering design research domain appear weak. Policy makers are an important audience for industry as they determine the environmental regulations that the companies will have to meet, and they are an important audience for the engineering design research community as they dictate research funding priorities. Developing a stronger interface with the policy research community is therefore seen as key to the on-going support of eco-innovation research, but also in ensuring that the knowledge and insights available within this community are considered during the formulation of policy measures.

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