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Integrating sustainable development in the supply chain: The case of life cycle assessment in oil and gas and agricultural biotechnology

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Abstract

It is widely accepted that firms play an important stewardship role in addressing sustainable development concerns. A key challenge in this role is to balance the often conflicting pressures created by sustainable development—firm-level economic performance versus environmental degradation and social disruption. Drawing on complexity theory, risk management, stakeholder theory and the innovation dynamics literature, we discuss the problems of integrating sustainable development concerns in the supply chain, specifically the applicability of life cycle assessment (LCA). Many authors have emphasized the importance of the ‘‘cradle to grave’’ approach of LCA in optimizing closed-loop supply chains, improving product design and stewardship. Based on two case studies (an agricultural biotechnology and an oil and gas company) with supporting data collected from key stakeholders, we argue that sustainable development pressures have increased complexities and presented ambiguous challenges that many current environmental management techniques cannot adequately address. We provide a framework that addresses these deficiencies and discuss implications for practitioners and management theory.

Keywords: Life cycle assessment; Sustainable development innovation; Complexity theory

1. Introduction

It is widely recognized that firms play an important stewardship role in addressing sustainable development pressures, and such concerns have become part of many companies' operational and competitive strategies (Angell and Klassen, 1999; Bansal and Roth, 2000; Hart, 1995, 1997; Hart and Milstein, 1999; Porter and Van der Linde, 1995; Shrivastava, 1995; Sharma and Vredenburg, 1998). A number of authors have emphasized the importance of such tools as life cycle assessment (LCA) to optimize closed-loop supply chains as well as improve product design and stewardship (e.g. Krikke et al., 2004; Sarkis, 2001; Sroufe et al., 2000). The ‘‘cradle to grave’’ approach of LCA that extends throughout the supply chain represents an evolution over environmental assessments focused on firm-specific impacts and end-of-pipe analyses, and is now part of many organizations' broader sustainable development efforts (Mihelcic et al., 2003). Such an approach is theoretically elegant when key interacting variables and boundaries of responsibilities are well understood. Unfortunately, such situations are rare, while the benefits from sustainability efforts have been

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elusive (Bowen et al., 2001; Hall and Vredenburg, 2003; Walley and Whitehead, 1994). In reality, practitioners continue to grapple with how and when LCA should be applied, due to the complexities and uncertainties of environmental systems involved, imperfections of human reasoning and impossibility of ideal societal decisions (Funtowicz and Ravetz, 1992; Hertwich et al., 2000; Allenby, 2000). In the operations management area, specific challenges of closed-loop supply chains may be intensified by complexities associated with product, remanufacturing, testing, evaluation, returns volume, timing and quality (Guide et al., 2003).

Because of complexity, decision-makers are limited in what they can know (bounded rationality) and thus rational calculations cannot guarantee optional solutions (Simon, 1962, 1969). These difficulties are exacerbated when dealing with novel and complex technologies such as genetic technology, because they involve science that has yet to be established within an accepted paradigm (Kuhn, 1970). New technologies may also create new industry structures, require new regulatory frameworks, generate consumer uncertainty (Ansoff, 1957; Martin, 1994; Nelson and Winter, 1982; Rogers, 1994; Utterback, 1994) and suffer from 'liabilities of newness' (Stinchcombe, 1965). In these situations, uncertainties about possible environmental, health and social impacts are more salient (Hall and Martin, 2005). More complexities can be expected when dealing with sustainable development because it involves a higher number of interacting parameters (i.e. economic, environmental and social, the popular 'triple bottom line' (Elkington, 1998) diagram of three overlapping circles). Indeed, the seminal definition of sustainable development (WCED, 1987, p. 43), ''*meeting the needs of the present generation without compromising the ability of future generations to meet their own needs*'' emphasized the temporal and dynamic aspect of sustainability, thus exacerbating complexity.

According to Hall and Vredenburg (2003, 2005), innovating for sustainable development is also usually more ambiguous, i.e. when it is not possible to identify key parameters or when conflicting pressures are difficult to reconcile. Such ambiguities make traditional risk assessment techniques unsuitable, as the estimation of probabilities through for example actuarial sciences, surveys, simulations and cost–benefit analysis would be based on unacceptably high degrees of imperfect information. They further argue that sustainability concerns frequently involve a wider range of stakeholders, many of whom are not directly involved with the organization. Decision-makers are thus likely to have significant difficulties in dealing with sustainable development. A better understanding of complexity and ambiguity may allow practitioners to determine the appropriateness of LCA in the extended supply chain.

According to Simon (1962), a complex system is characterized by a large number of interacting parameters, and it is difficult to infer properties of the entire system. Interdependence (positive or negative) and intensity (interaction strength) alternate with time, as well as parameter importance (Ethiraj and Levinthal, 2004). Related to complexity theory is the biological concept of fitness landscape (Wright, 1932), a distribution of possible genotypes (i.e. fitness values) mapped from an organism's structure to its fitness level. Kauffman (1993) argues that a landscape can be more or less rugged depending on the distribution of fitness values and interdependences among the parts—the more complex a system, the more rugged the landscape.

A number of management studies have applied Kauffman's concepts, such as Frenken (2001) for product evolution, Rivkin (2000) for firm development, Rivkin and Siggelkow (2003) and Levinthal and Warglien (1999) for organizational design, Gavetti et al. (2005) for strategic analysis, Choi et al. (2001) and Choi and Krause (in press) for supply chain management and Wolter (2005) for industrial cluster coordination. In general these studies argue that smooth landscape designs (low interdependence) result in relatively stable and predictable behaviour. Conversely, rugged landscape designs (higher interdependence such as diversification of functional teams) lead to greater exploration of possibilities of actions, at the cost of increased difficulties in coordination. Here we expand on Choi et al. (2001) and Choi and Krause (in press) application of complexity theory to supply chain dynamics by analysing its integration with sustainable development parameters.

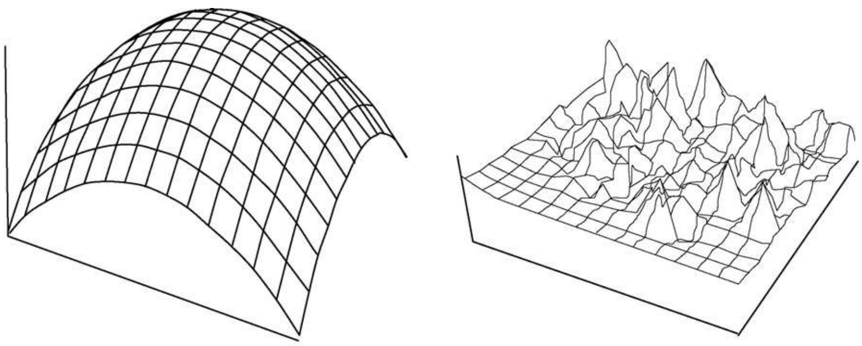
We consider sustainable development an inherently rugged landscape that requires coordination of social, environmental and economic dimensions. Environmental tools such as LCA should thus be 'connected' with social and economic dimensions, and is only meaningful if applied as part of a decision-making process and not a ''disintegrated aggregation of facts'' (Hertwich et al., 2000, p. 15). The use of LCA explored in this paper thus differs from other operations and general management literature, which discusses LCA disconnected from social issues (e.g. Bovea and Wang, 2003; Geyer and Jackson, 2004; Mehalik, 2000; Mattheus, 2004; Sarkis, 2001). A key difficulty is the decision-maker's limitations to deal with uncertainties and ambiguities, i.e. the level of interdependence among the dimensions and the degree to which key input and output parameters cannot be determined. Generally, such abilities are inversely correlated to the degree of novelty and complexity of the product or process under analysis. One technique that helps decision-makers and designers deal with such complex systems is modularization, a process that consists of identifying parameters, their role in the completion of the design and the degree of interdependences.

We start this paper by reviewing the literature on complexity theory, fitness landscapes and modularity to better understand how to deal with the difficulties of complexity. We then discuss the risks and complexities of sustainable development innovation, particularly in the context of stakeholder management. Stakeholder theory has been well established in the sustainable development discourse, while more recently the complex and sometimes ambiguous nature of certain stakeholder relationships have exacerbated sustainable development efforts (Hall and Vredenburg, 2003, 2005). Next we discuss our research methodology, followed by an examination of LCA for environmental management (a relatively restricted scope of analysis) and sustainable development (a relatively more complex scenario with interrelated parameters). We then present two polar cases (Eisenhardt, 1989) to better understand issues regarding the integration of sustainable development in the supply chain through LCA. The first concerns the application of LCA in oil production from bitumen in the Athabasca Oil Sands, Canada's largest carbon-based energy source. The second case discusses the applicability of LCA to agricultural biotechnology and a company's attempts to introduce their technology in a developing country. These cases show a clear contrast between an integrative and a myopic landscape model of LCA application. In the first case, LCA is applied using cross-functional teams to assure diversity of skills, addressing economic, environmental and social concerns, and their interactions. In the second case, although there are clearly links between environmental and social concerns, LCA is conducted addressing relatively well-known environmental parameters, disregarding cross integration with social and economic factors. Drawing on both environmental science and management perspectives, we present a preliminary framework for adaptive search towards sustainability of technologies that considers the appropriateness of LCA. We conclude with implications for managers, LCA practitioners and academic research in sustainable development.

2. Background

2.1. Complex systems and landscape theory

According to Kauffman (1993), fitness landscapes can be described by two structural parameters, $\boldsymbol{N}$, the number of elements ($\boldsymbol{a}_1, \ldots, \boldsymbol{a}_N$) that characterize the entity, and $\boldsymbol{K}$, the number of interactions that each element $\boldsymbol{N}$ is subjected. For a simple example, an entity can be a chair, with $\boldsymbol{N}$ elements or parameters such as material, colour, height, weight and resistance. Choi et al. (2001) and Rivkin and Siggelkow (2003) regard an organization as the entity, with $\boldsymbol{N}$ design elements such as type of relationship with suppliers (e.g. long versus short term, control versus emergence), incentive system, accounting methods, quality of employee effort and physical layout. We suggest that an entity can also be the sustainable development policy of a company. In this case, $\boldsymbol{N}$ can include a company's environmental, economic and social indicators. The parameters and their interactions make up the dimensions (or map) of an imaginary landscape, which represents all combinations of parameters (Baldwin and Clark, 1999). The lower the $\boldsymbol{K}$, the smoother the landscape, with no interaction when $\boldsymbol{K} = 0$ (Fig. 1a). Alternatively, as interactions increase and one choice



(a) Single peak design (smooth landscape) (b) Multi-peak design (rugged landscape)

Fig. 1. Landscape fitness according to the degree of interactions (Levinthal and Warglien, 1999).

of parameter influences the appropriateness of others, the landscape becomes more rugged or multi-peaked (Fig. 1b).

In Choi et al.'s (2001) application to supply chain management, $\boldsymbol{K}$ represents the number of interactions between individuals, project teams or organizations. If $\boldsymbol{K} = 0$, then actors behave independently. The maximum level of interaction for each parameter is $\boldsymbol{K} = \boldsymbol{N} - 1$. One point in the landscape corresponds to a particular combination of choices for the parameters that differs at least one choice from all other possible combinations. The peaks mean that the combinations work. For example, if a particular choice made for the interacting parameters $\boldsymbol{a}_1$ and $\boldsymbol{a}_2$ produce a positive result in terms of success of the design of an organization, then that combination fits. No peak means that the combination does not fit. Therefore, in this fitness landscape, the challenge is finding the higher peaks, i.e. combinations of parameters that work better than others.

According to Baldwin and Clark (1999), one way to address complexity is modularization, particularly when identifying interdependences and recognizing multiple and potentially conflicting pressures or decisions. Some of the key concepts of modularity can be observed through the matrix of interaction of an entity with 12 parameters ($\boldsymbol{a}_1, \ldots, \boldsymbol{a}_{12}$) shown in Fig. 2.

The x's represent interdependence among the parameters, for example, $\boldsymbol{a}_1$ is affected by $\boldsymbol{a}_2$, $\boldsymbol{a}_3$, $\boldsymbol{a}_4$ and $\boldsymbol{a}_{11}$. The matrix also indicates that interactions are stronger within certain groups of parameters, forming three distinctive modules represented by the shaded areas; module $1 = (\boldsymbol{a}_1, \ldots, \boldsymbol{a}_4)$; module $2 = (\boldsymbol{a}_5, \ldots, \boldsymbol{a}_8)$; module $3 = (\boldsymbol{a}_9, \ldots, \boldsymbol{a}_{12})$. Note that there is some interdependence between modules represented by the x's outside shaded areas. For example, modules 1 and 3 are somewhat interrelated by the interdependency between parameters $\boldsymbol{a}_1$ and $\boldsymbol{a}_{11}$. One other relevant aspect is the hierarchy among parameters, i.e. some parameters can only exist if specific choices about others are made first. In the chair example, all parameters related to the "arms", such as length, thickness, shape, material and colours would only be considered if the decision-maker chose that the chair would have arms. Hierarchy then allows decision-makers to delimit or expand the landscape of combinations by switching on or off certain parameters. Baldwin and Clark (1999) call this 'Design Structure Matrix' (DSM), with three characteristics:

- the list of parameters that describes the entity;
- the hierarchical relationships;
- the relationships between the structural elements (the interdependences, whether physical, logical or informational) among parameters.

Crucial to modularity is the design task, choosing the parameters that the entity will incorporate. Tasks can be, for example, set $\boldsymbol{a}_1$, set $\boldsymbol{a}_2$, and are performed by actors (e.g. Manager A chooses $\boldsymbol{a}_1$). In supply networks, modularization of work tasks may be applied to reduce the number of peaks by combining them into a few large peaks, "*creating a condition more conducive to optimizing the overall system*" (Choi et al., 2001, p. 362). Similar to the DSM, there is a task structure matrix that lists tasks and coordination links between actors. For example, if tasks A and B are performed by different people, then these two people must communicate with each other before making their final choices.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}
a_1		x	x	x							x	
a_2	x		x	x								
a_3	x											
a_4	x	x	x									
a_5						x	x					
a_6		x			x		x	x				
a_7					x	x		x				
a_8					x		x					
a_9										x	x	x
a_{10}							x		x			
a_{11}	x								x	x		x
a_{12}										x	x	

Fig. 2. Matrix of interactions.

The cost of not doing so could result in the failure of finding a sufficiently high peak. Baldwin and Clark (1999) also note that these two matrixes are isomorphic since the nature of interdependences determines what has to be done to complete the design. They further note that another important factor includes how parameters and interdependences are identified. One possible way is to *deduct* the parameters and interdependences by examining the entity. It thus requires accepted theory and a codified form of knowledge. The alternative is to *induce* the parameters and interdependencies by seeking out actors and asking what parameters would be selected, and whose decisions would be needed in order to make a decision. This approach requires tacit knowledge. Naturally, limitations exist and are determined by managerial knowledge and capacity of understanding complexity.

If we apply the concept of complexity theory to sustainable development, we can have a fitness landscape as a mapping of a set of parameters related to sustainability dimensions (i.e. economic, environmental and social). For example, fitness could be the combinations of quantitative parameters (e.g. emissions, production and costs) and qualitative parameters (e.g. stakeholder engagement, consumer satisfaction and trust) that contribute towards the success of the policy. The global peak (albeit in principle unknown) would then be an overall high sustainable development performance. If we view the sustainability landscape as smooth topography, i.e. as being comprised by economic, environmental and social parameters that are independent, no decision will affect other choices and actions. It thus does not matter which technique is applied to reduce for example air emissions, how much production will be expanded, what type of relationships are established with suppliers or whether relations will be built with local communities, as each decision for each dimension improves the firm's sustainability efforts by improving locally its own fitness. Using the landscape fitness metaphor, the overall maximum can be reached by moving to any point, as long as the point represents higher performance (Fig. 1a), or 'walking' towards a better position, i.e. uphill.

Note that there are positive and negative sides in both types of landscape. For example, Levinthal and Warglien (1999) argue that while a smooth landscape is easier to manage, it provides less room for new ideas and explorations, whereas a rugged landscape is more difficult to manage but allows for diversity and exploration. Of course, there are products and activities that do not require explorations of rugged landscapes and only incremental refinements are needed. They also emphasize that a landscape can be 'smoothened' by tuning down, or manipulating for example, distance, social and geographical factors. They suggested that once knowledge is acquired, some interdependence among parameters can be restored and the landscape can be smoothed. According to Levinthal and Warglien, search patterns will change during the evolution of the landscape, and thus move towards more incremental searching.

Interdependence among social, economic and environmental factors is the core of sustainability (Elkington, 1998). An LCA (or any other environmental tool) that focuses on environmental parameters disconnected from social concerns may therefore be counterproductive to overall sustainability goals. Note however that it is very difficult to understand interdependencies when social factors are involved, and most studies do not attempt to do so. For example, Handfield et al. (1997), Melnyk et al. (2003) and Zhu and Sarkis (2004) have shown that environmental practices positively affect the firm's operational performance, but they do not look at social factors. Azapagic and Clift (1999) only discuss interdependencies among environmental and economic parameters, arguing that optimization techniques can satisfy both environmental and economic criteria for improved product performance over the life cycle. O'Brien et al. (1996) is one exception that attempts to incorporate social concerns. However, their proposed LCA assessment that includes consulting a wide range of environmental and social stakeholders presents methodological difficulties, because they fail to recognize different interests and/or beliefs that are difficult or impossible to reconcile. With the exception of O'Brien et al. (1996), we depart from these studies by considering social factors in the application of environmental tools, specifically the case of LCA.

2.2. The risks and complexities of sustainable development

Managing risk is widely recognized as a core business function. In most cases, the issue concerns the probability and magnitude. Knight (1921) distinguished between probabilistic *true risk*, where both parameters and probabilities are known, and *uncertainty*, where the parameters may be known, but not outcome probabilities. From a managerial perspective, true risk is rare (perhaps limited to the gambling industry). Managing uncertainty is arguably the dominant corporate task, with considerable resources being allocated to converting uncertainties into probabilities through such techniques as actuarial sciences, market surveys, simulations and experiments (Hall and Vredenburg, 2004). *Ambiguity* is a situation where neither the parameters nor probabilities can be identified or estimated. According to Alvesson (1993: 1002), ambiguity may lead to "*... contradictions that can not be resolved or reconciled, absence of agreement on boundaries, clear principles or solutions ... Ambiguity is different from uncertainty while it cannot be clarified just through gathering more facts. Ambiguity means that the possibility of rationality – clarifying means-ends relationships or exercising qualified judgement – becomes seriously reduced.*"

Ambiguity, particularly the inability to identify key stakeholders and potential social outcomes, is becoming an increasingly important challenge, yet one insufficiently addressed by traditional management approaches (Stone and Brush, 1996). This is particularly the case for sustainable development because it may be difficult to identify not only interdependences among parameters but also the key parameters. For example, Hall and Vredenburg (2003) argue that sustainable development pressures, especially social issues, can be conflicting or difficult to reconcile, particularly if the technology is based on new science or has radical impacts on those that use or are affected by the technology. Moreover, sustainability often involves a wider range of stakeholders, many of whom are not directly involved with an organization carrying out an analysis.

Freeman (1984) makes the distinction between primary stakeholders, those with a direct interest in the organization (e.g. customers, shareholders, employees, suppliers and regulators) and secondary stakeholders, those that are not engaged in transactions with the organisation but can affect, or are affected by the organization (e.g. academic institutions, NGOs, neighbours and social activists). Similar to the stakeholder concept, Choi et al. (2001) makes the distinction between agents and the environment in the supply network. They define an agent as "*an individual, a project team, a division or an entire organization*" and environment as "*end consumer markets that exert demand for products and services provided by the system network (SN), directly or indirectly connected economic systems and the larger institutional and cultural systems that both define and confine the SNs interpretation of reality and its subsequent behavior*" (Choi et al., 2001, pp. 352–353). To avoid confusion with the natural (ecological) environment, we refer to agents as primary stakeholders and environment as secondary stakeholders.

Freeman (1984) and Clarkson (1995) recognize the often subjective interpretation of stakeholder concerns, particularly secondary stakeholders. Mitchell et al. (1997) expand on these arguments by recognizing the dynamic and interdependent nature of stakeholder relations, based on varying degrees of legitimacy, urgency and power. Such interdependencies imply that landscape topography changes and deforms as other actors' adaptive efforts change as a result of the changes made by actors with whom they are linked. For example, a company's policies may adapt to social pressures and then once an innovation is introduced, new social pressures may emerge. For example, in traditional crop production, most risk evaluations are based on scientific environmental concerns such as eco-toxicity, water use and energy consumed, whereas in biotechnology crop production environmental activists' campaigns have heightened consumer concerns over risks such as non-target effects, decreased biodiversity, allergies, and the impact on subsistence farmers. According to Levinthal and Warglien (1999), synchronization of behavior across organizations is crucial to facilitate cooperation. They further argue that it is important to ensure that improvements are globally distributed; when actors only consider payoff implications of their local actions and ignore the entire topography of the landscape, they 'myopically adapt' and only see illusory improvements.

3. Methodology

A grounded theory approach (Glaser and Strauss, 1967) was used to explore issues about integrating sustainable development in the supply chain. We applied theoretical sampling in selecting the case studies (Denzin, 1970), choosing different industrial sectors (agriculture, energy, chemicals and forestry) and countries (Brazil, Canada, China, The Netherlands, UK and US) to highlight theoretical issues (Eisenhardt, 1989; Glaser and Strauss, 1967). We examined a large number of cases to ensure differences in context and approaches towards sustainable development and thus increase the potential robustness of the theory induced from the results. The sectors chosen are under strong, albeit varying, sustainable development pressures which in some cases have pervasive implications that may trigger radical innovation (Tushman and Anderson, 1986) or 'creative destruction' (Hall and Vredenburg, 2003; Hart and Milstein, 1999; Schumpeter, 1942; Senge and Carstedt, 2001). Each case included an analysis of primary stakeholders such as suppliers, customers, competitors, technology consortiums, complimentary innovators, policy makers and regulators, and secondary stakeholders such as environmental groups, social advocates, community representatives and safety advocates.

3.1. Data gathering and analysis

The data presented in this paper is drawn primarily from Brazil, Canada and the US, with complementary data from other countries and inter-governmental organisations. Semi-structured interviews with 135 industry representatives and other key stakeholders, 4 focus groups with Brazilian farmers (totaling 48 participants) and observations of 3 LCA workshops (45 participants) were conducted between 2002 and 2005 (Appendix A). Interview subjects were identified through literature searches, industrial contacts, web-pages and the snowball technique (Vogt, 2005) to identify other key subjects. Interviews were conducted in each organization in-person using an open-ended format, using a list of questions (Appendix B) to open the discussion, but not to limit the interviewee's scope for raising relevant issues. For example, we enquired about the main issues in their industry sector, their policies towards sustainable development and key stakeholder interdependencies. All members of the research team were responsible for the identification of appropriate firms, subjects and interviews. Following interviews, the team discussed, reviewed and summarized the data, facilitating data analysis and identification of opportune findings (Eisenhardt, 1989).

Once potential propositions were identified, we analyzed complexity theory, risk management and the innovation dynamics literature to further understand integrating sustainable development in the supply chain and LCA applicability. Follow-up interviews were conducted to extend, triangulate and focus the research (as reflected in more interviews in the energy and agricultural sectors). For example, we asked about firm-level approaches to sustainable development and for descriptions of LCA approaches, including which variables were considered. To avoid leading, we only asked at the end of the interview if social and economic variables played a role in LCA implementation, and if any interactions were considered among these variables (see Appendix B). As in the first phase of the research, interviews were recorded and summarized. We also observed three LCA workshops concerned with the oil and gas case and four focus groups (Morgan, 1997) concerned with the ag-biotech case.

Two cases were selected to provide examples of polar situations (Eisenhardt, 1989), offering insights regarding the appropriateness of LCA in complex and ambiguous systems, and how such tools may integrate sustainable development in the supply chain. The first case is based on a Canadian oil and gas company exploiting the Athabaska oil sands in Northern Alberta, Canada, one of the world's largest fossil fuel reserves in an environmentally and socially sensitive area. They were successful in their LCAs because they recognized the importance of interdependencies among parameters. The second case concerns a US-based multinational's attempts to introduce genetically engineered (GE) soybeans to Brazil, the world's second largest producer of soybeans. Brazil is less economically developed, has higher rates of poverty and other social constraints, and thus offers useful contrasts for understanding sustainable development pressures. The multinational's approach to sustainable development underestimated the importance of parameter interdependencies, and they encountered major difficulties with technology acceptance.

4. LCA for environmental management—a single-peak landscape?

LCA has been widely used to answer questions on the environmental implications of a product, from raw material collection to final disposal, recovery or recycling, what Guide et al. (2000) call a recoverable manufacturing system. Although LCA is a relatively new analytical tool and advances continue to be made, there is a general consensus in the International Organization for Standardization ISO 14000 series framework (Rebitzer et al., 2004). The goal and scope definition phase includes establishing study objective(s), functional units (a basis that enables comparison and analysis of the results) and system boundaries, i.e. defining the boundaries between the life-cycle system of the selected product and the connected life-cycle systems of other products. Inventory analysis involves estimating resource use and pollutant releases into the air, water and land attributable to a product's life cycle (Rebitzer et al., 2004). Impact assessment involves assessing inputs and outputs in order to evaluate contributions of inventory data to various potential impacts (Pennington et al., 2004). Finally, findings are interpreted and compiled as recommendations for decision-makers. The interpretation phase interacts with all other steps of LCA. In some situations, practitioners may find the comparison of material consumption for two products sufficiently conclusive. In this case, interpretation is based on the inventory phase.

Hertwich et al. (2000) argue that decisions made throughout a LCA should consider public concerns and take into account bounded rationality as well as the complexities and uncertainties of natural science. For example, a practitioner may want to prioritize product alternatives or resolve trade-offs such as lower climate change indicators for one option but higher toxicological indicators for another. The decision may be difficult, as it considers the economic and social implications of choosing one option over the other. This situation represents a rugged landscape because the interdependencies among environmental, social and economic decisions may be high. However, in practice, most decisions are made based on economic and environmental criteria (and perhaps in this order), as practitioners usually do not recognize the importance or do not know how to deal with social factors (Cowell et al., 2002).

Because value judgements are involved in several steps (e.g. different choices of boundaries, Carlson-Skalak et al., 2000), different approaches might lead to different results. These differences have generated criticism regarding LCA reliability, hence the importance of uncertainty and sensitivity analysis to evaluate and enhance credibility. Much has been discussed about the challenges of the impact assessment phase because of the complexities and limitations in data gathering and scientific analysis. According to Hertwich et al. (2000), most problems in LCA methods can be addressed as long as they are consistent with its goals. Meaningful goals, especially when the study is meant to be part of sustainable development efforts, require coordination with other economic and social teams.

Most LCAs consider environmental emissions independent from the place and time that they occur (i.e. generalized emissions rather than site specific data are used). However, some more comprehensive (and expensive) studies use site-specific, albeit limited data, aiming to analyze more accurately the receptors and substances to which they are exposed (Hogan et al., 1996; de Haes, 1996). Obviously new technologies or processes may require surrogate data, as there may be no precedent specific knowledge about potential hazards. Using surrogate data simplifies the process at the expense of increased uncertainty. Note that uncertainties are modeled (i.e. probabilities are estimated or assigned). In fact, LCA considers both technical and non-technical uncertainties (value judgments) through quantitative analysis (Huijbregts et al., 2003; Heijungs, 1996; Steen, 1997; Kennedy et al., 1996). Technical uncertainties in LCA are treated with methods similar to risk assessment such as classical probabilistic uncertainty analysis using the Monte Carlo technique (EPA, 1997), which consists of generating a distribution function for the results using 'best estimate values' and assumed distribution for each parameter on which the results depend.

Non-technical uncertainties in LCA are treated with probability assignment techniques or a combination of probabilistic and cultural uncertainty analysis techniques. Huijbregts et al. (2003) for example suggest that uncertainty in assumptions and judgements can be analyzed using Monte Carlo simulations in a three-step process. First, alternative scenarios are considered. For example, scenarios with a time horizon of 20, 100 or 500 years, low or high waste recycling rates and different impact categories. Second, probabilities are assigned in order to express the (rationally bounded) faith of the modeller in a particular scenario or model formulation (e.g. 25% little credence, 50% medium credence, 75% high credence). Finally, the resulting output distribution is obtained by Monte Carlo analysis to reflect the uncertainty of the decision-maker's choices. They thus treat non-technical and technical uncertainties similarly.

Regarding the choice of scenarios (a particularly contentious value judgement area in LCA), Hofstetter (1998) suggests Cultural Theory, which attempts to systematically address the complexity of different individual perspectives at a general level (Marjolein et al., 2002). Four perspectives, or archetypes, with somewhat predictable behavior are recognized: hierarchist, egalitarian, individualist, and fatalist. They differ according to for example values, rationality, risk propensities and management styles. These perspectives are thus used to generate different scenarios of LCA as they offer a structure to predict societal preferences, i.e. possible outcome choices and value judgments. For example, Frischknecht et al. (2000) conducted a LCA study applying different perspectives. From an egalitarian's perspective, they assumed a 100,000-year time horizon for exposure, as egalitarians regard exposure in the future equally important as exposure today. One hundred years was the assumed time horizon for the individualist scenario, as the present is what counts for this archetype. The application of such value judgements to all parameters in all LCA phases would lead to three alternative routes (and respective uncertainties) of impact assessment scores or indices (Hofstetter, 1998).

Note that LCA analyses are conducted using parameters that are known and the behaviour probabilities are predictable (Tukker, 2002). This approach gives a relatively smooth landscape with a large number of parameters but small number of interactions. The recognition of nontechnical uncertainties and subjective criteria thus present a reliability paradox. On the one hand, applicable non-technical issues are being addressed, yet simultaneously the subjective nature of such approaches may reduce LCA reliability. Some companies have found LCA inappropriate and chose to develop their own analytical techniques (Allenby, 2000). A senior executive interviewed stated that they preferred not to conduct a LCA for this reason, believing that it can be easily manipulated to address specific interests and may generate managerial scepticism towards LCA. Another vice-president stated: "*LCA is an academic exercise*, *it is not practical*. *It is too complicated and expensive and companies have stopped talking about that*."

Furthermore, these uncertainty analyses do not recognize the realities of imperfect information: how does one know which stakeholders matter and what choices and value judgements they are going to make? According to Hall and Vredenburg (2004), it is common for secondary stakeholders concerned about sustainability issues to show up unexpectedly and affect the company's performance.

Not all situations require a rugged landscape. Although the idea of using only known data seems to be inappropriate, there are systems that are well represented by a relatively smooth landscape. For example, a US-based adhesives company has been successful with LCA studies in this manner. According to a senior environmental manager and a LCA specialist, their LCA approach is conducted independently from their corporate social responsibility department. In fact, a tempting approach is to transform a rugged landscape into a smooth one, i.e. to simplify the system by turning some parameters and interactions off, so the fitness can be reached more easily. However, the key point of this approach is that decision-makers must have reasonable confidence that those simplifications will not compromise the search for high performance, as was the case for the adhesives company. We postulate that this confidence is due to path dependent, accumulated experience (Arthur, 1987), particularly regarding stakeholder engagement (Sharma and Vredenburg, 1998). Kauffman (1993) suggests that the main features of a single-peak landscape also can be preserved in a low interdependence setting. In this situation, $\boldsymbol{K}$ is much lower than $\boldsymbol{N}$, and lower peaks will tend to lie in peripheral regions of the higher peak. Although adaptive walks toward the highest peak will no longer be guaranteed, the probability of reaching a satisfactory peak through local improvements is high (Ethiraj and Levinthal, 2004).

We suggest that if LCA is applied only in the context of environmental management, the landscape can be 'smoothened', but its meaningfulness will depend on decision-makers' confidence about the system's low degree of complexity. However, if LCA is applied in the context of sustainable development, then it may be much more difficult to disregard interdependences. As pointed out by Hertwich et al. (2000), environmental effects are externalities that affect economic *and* social goods, yet these interrelations are difficult to identify.

5. LCA for sustainable development—a multi-peak landscape?

As discussed above, the management literature has emphasized the increasing importance of sustainable development in firm behavior. However, it was also noted that sustainability for many firms has been difficult, due in part to high degrees of ambiguity and complexity. Under such circumstances, managers cannot fully understand the implications of how the parameters interact, which may lead to compromises or less than ideal options (Frenken, 2001; Gatignon et al., 2002), or increased political influences (Rosenkopf and Tushman, 1988). Environmental issues often involve considerable complexities because of the very nature of ecosystem interactions (Wolfenbarger and Phifer, 2000). Sustainable development is that much more complex, because it involves interactions amongst environmental, economic and social parameters. According to one senior manager: "*One of the main challenges is to find a balance between the* 3 *pillars of sustainable development*. *We are particularly under pressure from local communities for jobs*." Furthermore, it is often difficult to identify key parameters such as activist groups. As secondary stakeholders do not always have the same rights, claims or interests as primary stakeholders (Clarkson, 1995), they may present conflicting or difficult to reconcile pressures that are hard to identify at the early stages of product development (Hall and Vredenburg, 2003). The managerial pressures of sustainable development are thus a rich mix of technical and nontechnical issues. In this situation, disregarding interdependences with confidence becomes difficult. Since $\boldsymbol{K}$ (the number of interactions) may be large, reaching a satisfactory hilltop becomes difficult; as decisions are made (i.e. one begins to climb the hill) a large number of possible configurations emerge. Therefore, feedback that helps individuals recognize fitness gradients (whether positive or negative) becomes ambiguous, as many parties have contradictory demands. The adaptive walk towards a satisfactory peak is thus not guaranteed (Levinthal and Warglien, 1999). Sustainable development is thus a rugged landscape.

Although companies increasingly recognize that social factors may affect the development of new technologies or products, there has been little guidance on how to deal with such factors. According to Hall and Martin (2005), traditional frameworks for evaluating innovations consider primary stakeholders, focusing on technological and commercial viability and the firm's ability to appropriate the benefits of their investment. However, they suggest that social aspects must also be considered when introducing new technologies. A broader range of stakeholders such as activist groups, trade associations and religious organizations must be considered, and that these additional stakeholders present both complexity and ambiguity challenges. According to Bijker (1995, p. 15): "*a successful engineer is not purely a technical wizard*, *but an economic*, *political*, *and social one as well*. *A good technologist is typically a 'heterogeneous engineer*'." We will use this approach to analyse the case studies, and propose a framework to help managers adaptively walk through the rugged landscape of sustainable development and determine the appropriateness of LCA.

6. Case study analyses using the landscape metaphor

The following sections illustrate two cases of LCA applications, oil sand refining, an innovative process in the energy sector, and agriculture biotechnology, a technology based on a relatively new scientific paradigm that is raising a wide range of environmental, economic and social concerns.

6.1. Case 1: LCA application in oil sand operations

Steam separating technology for oil extraction from bitumen was first developed in the 1930s. In the 1960s, Company A began producing commercial synthetic oil from this expensive process. Since then, the company has undergone major expansions and invested heavily in incremental innovation, leading to reduced processing costs and a quadrupling of production. By 2004, they produced approximately 225,000 barrels per day, generating over C$8.5 billion in revenues and C$1 billion in net earnings that year. The company successfully expanded its expertise in other energy sectors, although most of their technological innovations are based on relatively accepted science rather than new scientific breakthroughs. A major player in oil sands development, they are regarded as mid-sized in the oil and gas industry.

Part of the company's success is due to high levels of environmental performance and strong relationships with secondary stakeholders, and they are consistently ranked on the Dow Jones Sustainability Index. According to the Vice President of Sustainable Development, their proactive stance towards sustainability emerged after a number of high profile spillages and complaints from secondary stakeholders led to drastic changes in the company. Other industry executives commonly cited such negative reputation-related pressures as a key reason why many Canadian firms engaged in a gradual, path dependent accumulation of sustainability capabilities. An important factor for this proactive performance (Sharma and Vredenburg, 1998) is that there has been an effort to integrate economic, environmental and social issues so that sustainability concepts become part of their activities, both within and outside the organization. As the company's activities are based on exploiting state-owned natural resources, the VP for Sustainable Development stated that the company must constantly demonstrate their contributions to society, requiring a 'social license' to operate. As part of this overall goal, all supply chain members are monitored and expected to behave in an environmentally and socially acceptable matter, and they have invested in supply chain initiatives to facilitate this behavior. They have also encouraged participation of local First Nations suppliers as a means of promoting social inclusion.

Company A treats sustainable development as a rugged landscape. They recognize interdependences among sustainability parameters and report them as integrated indicators. For example, they document the relationship between greenhouse gas emissions and company revenues and expenses. Incidents and regulatory contraventions are linked with environmental, health and safety and economic performance, as well as the company's reputation. In total, approximately 90 integrated environmental, economic and social parameters are listed in their annual report, although no details regarding parameter interactions are provided. Factors difficult or impossible to measure such as trust, reputation, and social concerns stay out of the report. However, both measurable and non-measurable parameters are considered in their LCA approach, which involves an integrative quantitative and qualitative analysis of environmental, social and economic aspects of new operations or expansions.

Parameters are identified during workshops for all new projects and evaluated by the company's employees from different departments, including representatives from the finance department, communications, health and safety, environment, external relations, project managers and engineers. These workshops are facilitated in conjunction with a subcontracted local technically trained NGO.

Our research included observations of three such workshops, where we closely examined this process of cross-integration. In order to guide participants through the analysis, the NGO facilitator starts by asking practitioners to indicate units of the manufacturing system for the new project, usually starting from the construction site, followed by operations of the firm and the extended supply chain, and ending with decommissioning. For each process, participants are asked to identify positive and negative economic, environmental and social factors. The diversity of participants' expertise assures a broad sustainability analysis and collective action towards identification of opportunities for improvements. Our observations indicated that they effectively influence the search behavior by identifying possible problems as well as finding solutions within a diverse team ('jump search' or non-incremental and exploration searching). Note that cross-organizational collaboration occurs through their relations with NGOs and other secondary stakeholders. In addition, as knowledge on effective walks accumulates over time, the location of a satisfactorily high peak becomes easier to estimate. As a result, the LCA is well integrated with their sustainability efforts.

In addition to technical inputs, the VP of Sustainable Development stated that the NGO relationship also provides strategically valuable attributes such as enhanced legitimacy of LCA results, thus reducing friction with secondary stakeholders. It also provides them with information regarding concerns from secondary stakeholders that may otherwise be overlooked, and buffer the company from more antagonistic activists in the NGO community. Westley and Vredenburg (1991) refer to such collaborations as 'stakeholder bridging'. For example, the company was once considering oil sands development in Australia. Greenpeace planned to embark on a major campaign to stop the development. The insider relationship with the LCA NGO provided insights into the anti-oil sands development movement. The NGO also pressured Greenpeace to hold back aggressive protests, arguing that Company A was one of the more progressive corporations.

6.2. Case 2: LCA application in agriculture biotechnology

Our other case is a leading biotechnology company with sales of over $US5 billion and $US250 million in net income in 2004. Company B developed novel technologies based on relatively new science, and were successful marketing their products in the US, but less so in Europe and the developing world. In this case, sustainability issues were particularly complicated, and knowledge about inter-related social and environmental parameters was insufficient. The system could therefore not be treated as a smooth landscape. Although technical, commercial and organizational factors were addressed, the impact of unknown environmental parameters was underestimated and social dimensions disregarded, which led to a series of setbacks during technology implementation in Brazil, the focus of this case.

From an environmental perspective, a review of existing scientific studies by Wolfenbarger and Phifer (2000) found that it is currently not possible to determine the benefits and hazards of GE organisms. This is mostly due to complexities associated with ecological systems and their epistatic interactions, metabolic systems and the risk of changing functional properties of the organism, changing bioactive compounds, epigenic silencing of genes, altering levels of antinutrients and potential allergens and toxins (Doerfler et al., 1997; Inose and Murata, 1995; Lapeé et al., 1999; Novak and Haslberger, 2000). LCA studies supported by Company B were conducted on GE technology with unknown variables disregarded. For example, Bennet et al. (2004) conducted a LCA to compare traditional versus GE beets. The results show that GE beets are more beneficial in terms of environmental and health impacts, specifically energy consumption, global warming potential, ozone depletion, eco-toxicity, acidification and nitrification. The study analyzed impacts over different herbicide spray regimes, and issues often addressed by NGOs such as gene invasiveness, allergies and unexpected effects were left out of the study.

Attempts have been made to set standards for risk assessment of GE organisms at a global level (UNEP, 2000). However, related uncertainties can only be overcome through long-term field studies on ecological hazards. As the technology was based on relatively new science, there were greater uncertainties concerning human and environmental consequences, and few opportunities to draw on long-term precedent data. Such problems are not necessarily beyond the scope of a

LCA but certainly suggest limitations: context specific data is considerably more expensive, while ecosystem dynamics are highly complex. Since so many environmental consequences remain unknown, it is not possible to conduct a comprehensive LCA without exacerbating the disagreement about uncertainties and interpretation of the results. Conducting a streamlined LCA (i.e. reducing the scope of analysis) would also not be useful because it does not address complex environmental issues. Indeed, in the presence of complexity, further LCA difficulties arise from different interpretations. For example, field trials conducted by UK researchers evaluating GE crops found a general negative effect on biodiversity (Brooks et al., 2003; Champion et al., 2003; Haughton et al., 2003; Hawes et al., 2003; Roy et al., 2003; Squire et al., 2003). However, GE maize crops presented more weed seeds than in the conventional maize fields, which led to higher diversity of animal life in the area. The anti-GE activists claimed that the findings reinforced a view that there is no benefit derived from GE technology, while much of the scientific community viewed the results as positive (Burke, 2003).

The review of hazards and benefits conducted by Wolfenbarger and Phifer (2000) also had different interpretations. For example, a chief technical officer in a biotech firm interpreted the review as not being detrimental, since in several years of commercial use no environmental problems were uncovered. Conversely, one NGO concluded from the same study that little is known about GE crops and therefore they should not be permitted (Löfstedt et al., 2002). All NGO representatives interviewed in our studies emphasized the importance of taking a precautionary approach when dealing with new technologies, while corporate interview subjects and other advocates of the technology countered that the precautionary principle could be used as an excuse to prevent technology development. For example, a manager in Company B stated: "*They* [*NGOs and other opponents*] *want to stop the technology using the precautionary principal. Political rivalry, anti-globalization . . .nobody is interested in health or environment, political reasons play an important role in this issue*."

From a technological and commercial perspective, the company's development of transgenic seeds resistant to their proprietary herbicides involved the accumulation of new scientific knowledge that could disrupt their previous knowledge base as well as those of their competitors, a difficult and risky activity (Afuah, 1998; Christensen, 1997; Schumpeter, 1934; Tushman and Anderson, 1986). The company was aware of these transition difficulties and was able to accumulate new scientific competencies without disrupting their suppliers, customers and complementary innovators (Hall and Vredenburg, 2003; Hall and Martin, 2005). For example, farmers and food producers did not need new competencies to use their products, and had initial success in their US markets, while a strong intellectual property protection regime and complementary assets (Teece, 1986) assured profitability. However, they were less successful in dealing with non-technical uncertainties, particularly secondary stakeholders. This had important implications, as they made a strategic decision to exploit sustainable development opportunities, promoting the technology with such slogans as 'Sustainable development for the world's future' in 1997, and 'Food, health and hope' in 1999. Making such claims implicitly legitimized environmental and social stakeholders and invited expression of their concerns.

Social uncertainties played a major role in the diffusion of the technology. For example, our interviews with farmers and non-industry stakeholders in Brazil (see Appendix A) identified concerns over small farmer rights such as local seed breeding knowledge/competence preservation and national sovereignty issues. A subsistence farmer stated (translated): *"If the transgenics are allowed in Brazil, the small farmers are the ones who will suffer."* A UN representative stated, *"What goes beyond the discussions here in Brazil, particularly in the NGO community* [*is that*] *the battle for them is not if transgenics are good for the body but if transgenics are good for the society.*"

Such concerns resulted in a split within Brazil, a major potential market for GE technology. Up until the Federal Government approved a contentious biotechnology bill in February of 2005, both Ministries of Environment and Agricultural Development (representative of small-scale farming) opposed GE technology, while the Ministry of Agriculture (representative of large-scale farming) and the Ministry of Science and Technology supported it. Evidence collected from interviews with senior industry managers, policymakers, consultants and NGO representatives in Brazil indicated that although there were technical uncertainties, the majority of the problems were non-technical and ambiguous. For example, all interview subjects indicated that the involvement of this particular company was perceived to be detrimental to the acceptance of the technology, as foreign multinationals could threaten national sovereignty and erode local small-scale farmer competencies, thus increasing the rift between rich and poor nations. Brazil, one of the last major exporters of GE-free soybeans in 2005, was also caught between pro-GE American and anti-GE sentiments in Europe. Both sides were using sustainable development concerns in an attempt to sway, but ultimately convolute the issue.

Although the emergence of social issues became salient, Company B failed to recognize interdependencies amongst economic, environmental and social parameters, and their sponsorship of a LCA study was not integrated with these broader sustainability concerns. In contrast to Company A, its application reflects a hierarchical decomposition of a problem where actors need only know parameters of neighboring components (i.e. within the environmental domain), and interactions that can be explained by the numbers.

7. Preliminary framework

In this section, we propose an analytical framework that addresses LCA appropriateness in the evaluation of complex and novel technologies for sustainable development. The framework consists of a matrix of sustainable development uncertainties based on Elkington's (1998) 'triple bottom lines' of economic, social and environmental sustainability pressures and Hall and Martin's (2005) framework for evaluating innovations, i.e. technological, commercial and organizational uncertainties concerned with economic performance, and social uncertainties concerned with environmental and social impacts. We divide Hall and Martin's social uncertainties into environmental and social uncertainties to reflect more accurately how LCAs are applied in practice. Parameters and related interdependences are "searched" during the life cycle phases of the product (here simplified using design, production, use and disposal), motivating cross-organizational integration with secondary stakeholders. Fig. 3 shows the proposed analytical framework.

Drawing on complexity theory and modularity discussed in Section 2.1, we establish a series of steps to identify parameters, interdependences and task hierarchies by building a matrix of interactions (Fig. 2). We also include questions to help the assessor

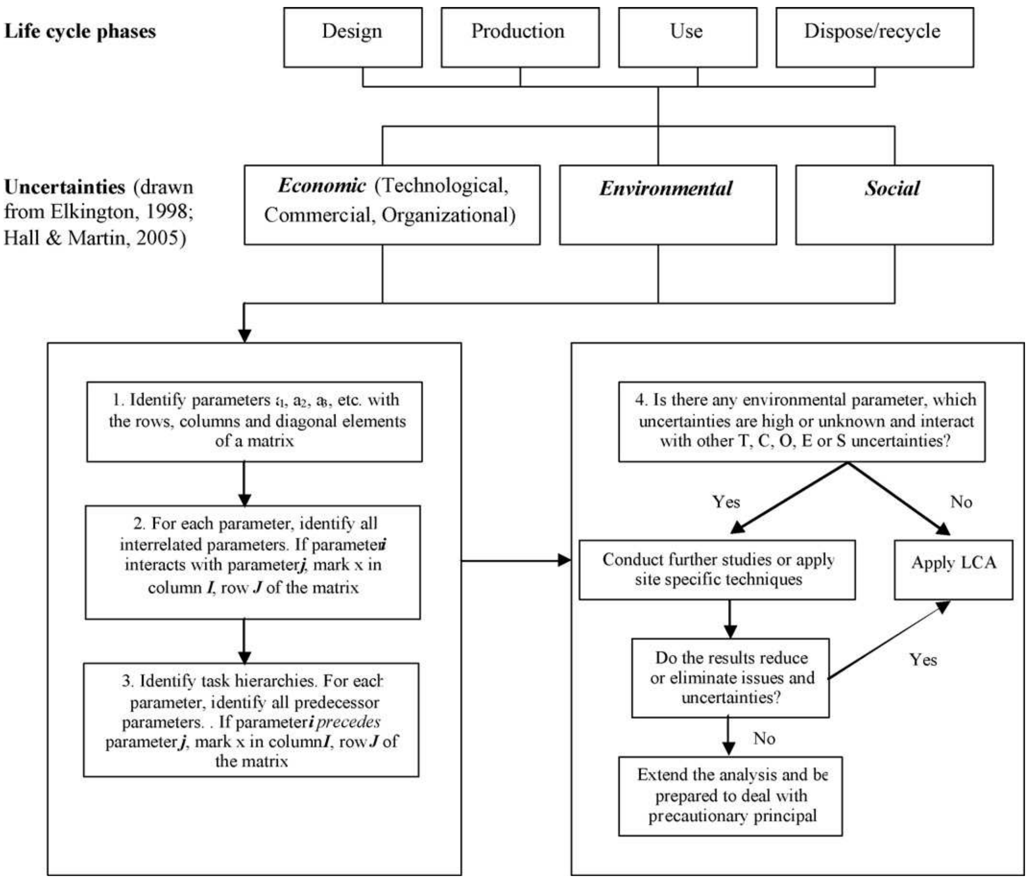


Fig. 3. Preliminary analytical framework for LCA appropriateness in the evaluation of complex and novel technologies for sustainable development.

Table 1
Examples of parameters derived from interview data

Economic			Environmental	Social
Technical	Commercial	Organizational		
Raw material processing	Markets, competition	Complementary assets (access to capital, market, internal expertise, economies of scale)	Air emissions	Jobs created
Chemical reactions	Price structure	Firm competencies, capabilities Intellectual property protection; other appropriability mechanisms	Water discharge quality	Knowledge enhanced/ transferred to local communities
Sub-products	Earnings		Energy consumption	Health and safety (e.g. employees injuries, fatalities)
Productivity	Cash flow operations		Water use	Health and safety of local communities
Processing time	Investment		Waste management	Equal opportunities and diversity (for woman, aboriginals, persons with disabilities)
Thermal properties	Capital expenditures		Land disturbance and reclamation diversity (for women	Potential negative side effect on or from secondary stakeholders
Durability	Purchases (goods and services)			Stakeholders engagement satisfaction
Weight				
Height				
Colour				
Reusability				

Representative but not intended to be comprehensive.

identify uncertainties in each dimension (economic, environmental and social). Although not intended to be comprehensive, the overall process should provide a reasonable structure to evaluate LCA appropriateness. The steps involved in developing the matrix are explained below, with examples of parameters listed in Table 1.

Framework steps:

1. List economic (technological, commercial, organizational), environmental and social parameters. Ask actors (e.g. employees from different departments, with different skills) involved ''What parameters would you consider?'' Note that these parameters do not have to be exclusively quantitative. Identify parameters $\boldsymbol{a}_1$, $\boldsymbol{a}_2$, $\boldsymbol{a}_3$, etc. with the row and column elements of a matrix.
2. Seek for interdependences. Ask ''If, there are any changes made in the parameter $\boldsymbol{a}_1$ (e.g. change package material from plastic to cardboard), what other parameters will also be changed?'' For each parameter, identify all interrelated parameters. If parameter $\boldsymbol{i}$ interacts with parameter $\boldsymbol{j}$, mark x in column $\boldsymbol{I}$, row $\boldsymbol{J}$ of the matrix.
3. Identify task hierarchies. Ask ''Whose decision do you need to know in order to make your decision?'' For each parameter, identify all predecessor parameters. If parameter $\boldsymbol{i}$ precedes parameter $\boldsymbol{j}$, mark x in column $\boldsymbol{I}$, row $\boldsymbol{J}$ of the matrix.
4. Identify uncertainties involved in each dimension. Ask actors involved:
   (a) *Technological uncertainty.* Is the technology feasible from a scientific and engineering perspective (i.e. does it meet technological performance criteria)?
   (b) *Commercial uncertainty.* Is the technology commercially viable?
   (c) *Organizational uncertainty.* Does the development of the technology fit with the overall strategy and capabilities of the firm, and can benefits be appropriated?
   (d) *Environmental uncertainty.* Are there any potential environmental impacts that are unknown or require specific investigation?

(e) *Social uncertainty.* Are there any potentially negative side effects on, or from, secondary stakeholders?

Note that questions provided here aim to illustrate how to use the framework, and practitioners should not restrict themselves regarding other pertinent, context specific questions. Questions 1–3 are clearly intended to identify variables and interdependences (Baldwin and Clark, 1999). As in the matrix of interactions explained in Fig. 2, stronger interdependences will be identified within each dimension forming distinctive modules represented by shaded areas. If interdependences between modules, i.e. among economic, environmental and/or social parameters are identified (which would correspond to the *x*'s outside the shaded areas as shown in Fig. 2), then it is important that the assessor consider analysing these parameters in the application of LCA (or any tool) that relates to the evaluation of their sustainable development performance. While such tasks may be difficult, it will allow managers to work on the more realistic landscape, and more broadly explore new ideas and possible solutions, as suggested by Levinthal and Warglien (1999). Outside *x*'s are thus a key factor of this framework.

Question 4 draws on Hall and Martin's (2005) approach to technology evaluation, which considers technological, commercial, organizational and social viability. This question thus is intended to check for uncertainties and, more importantly, to examine the degree of complexity regarding the case under consideration. If for example answers to questions 4d and/or 4e are yes, the assessor should consider clarifying environmental impacts and/or engage in stakeholder consultations before conducting a LCA. When analysing sustainable development performance, LCA may or may not be the most appropriate tool, depending on the ambiguity and the degree of interdependences among uncertain environmental parameters and other factors, such as social concerns. The alternative is to apply more narrowly focused studies and site-specific techniques. An example of this situation was found during our data collection. According to the environmental specialist of one company, in order to avoid having to react to "*Greenpeace's latest propaganda campaign* [*this company*] *decided to find a way to get more objective assessments of what the real issues are*, *rather then reacting to whatever the flavour of the moment might be*." The company then made efforts to understand two key environmental issues not addressed by LCAs at that time—organochlorine compound weighting factors and measurement of impacts on eco-biodiversity. Those studies were later made public and improved the reliability of LCA application in the forestry sector.

In summary, we suggest that a key challenge of a rugged landscape consists of seeking parameters and interdependences using both tacit and explicit knowledge from collaborative teams covering a diverse spectrum of skills and expertise. This collaborative team should be committed to share information in order to find a satisfactory combination of parameters—a high peak. If the degree of uncertainties and ambiguities can be reduced through such approaches, LCA can be applied and integrated within the company's sustainability efforts. If despite such efforts uncertainties and ambiguities cannot be reduced, then LCA may not be appropriate, and practitioners should engage in extended analysis or be prepared to deal with the precautionary principal. Part of this challenge thus consists of understanding the circumstances in which LCA is applied, and how LCA (including its goals, methods and interpretation) interact with sustainable development complexities.

8. Conclusions

Although it has been widely recognized that firms play an important stewardship role in addressing sustainability concerns, there remains considerable difficulties implementing this role. LCA is one tool initially developed to integrate environmental concerns throughout the supply chain into corporate decision-making, and more recently expanded to include sustainability concerns. This transition to the more complex and ambiguous nature of sustainable development has however created additional challenges in terms of applicability and resource requirements. In this paper, we have drawn on complexity theory, risk management, stakeholder theory and the innovation dynamics literature to illustrate these problems, and proposed a framework to help practitioners deal with them. We considered a rugged landscape as the most appropriate approach to search for high performance when dealing with sustainable development, which presents both obvious and not-so-obvious interdependences among environmental, social and economic parameters.

The three main points of the framework are identifying parameters and uncertainties, searching for interdependences and adapting through cross-functional walks. We used the concept of matrix of interactions and tasks to identify parameters and interdependences among economic, environmental and social factors. These factors analytically framed the appropriate dimensions of a potential technology towards sustainable development. The framework also helps managers determine if LCA is appropriate. For example, if there are any potential environmental or social impacts that are unknown or require specific investigation, the assessor should consider undertaking more narrowly focused studies by applying site-specific techniques before conducting a LCA.

Our two cases illustrate the appropriateness of LCA under different circumstances and approaches. Both were engaged in activities with wide-ranging social and environmental impacts. Company A was engaged in incremental technical change, where complexities were relatively easily reduced and manageable, allowing for satisfactory options. Due to operational maturity, key parameters, such as technological characteristics and secondary stakeholders could be identified. Their cross-integrative LCA approach was tailored and evolved to fit their sustainability policies. In contrast, Company B was exploiting relatively new science with many technical and social uncertainties, and most importantly a high degree of interactions amongst them. Such circumstances exacerbate the need to use cross-integrative approaches, yet the company failed to recognize the implications of these interactions, and any attempts at LCA would be heavily criticized. Note that Company A's relatively successful initiatives were provoked by a previously inadequate recognition of interactions among sustainability parameters. Their policies and ability to cope with these pressures changed considerably once these dynamics were recognized, emphasizing the importance of learning and path dependencies. With the maturing of ag-biotech, perhaps Company B's LCA initiatives will be more successful, providing they appreciate the importance of parameter interactions. Thus while technological differences matter, business factors, managerial approaches, a willingness to adapt and related path dependences are also crucial.

Recent trends in the literature have emphasized the importance of taking a broader perspective when dealing with product stewardship, including environmental impacts created by extended supply chain members, and LCA was explicitly developed for this purpose. However, as societal expectations shift from environmental issues to broader sustainable development concerns, isolated attempts to reduce environmental impacts are destined to provide less than optimal solutions or even counter-productive outcomes. The managerial challenge is thus to explore the interdependences amongst parameters in an attempt to identify satisfactory solutions. Our findings suggest that it is perhaps better to understand these interconnections moderately well (Company A), rather than having deep, but disconnected expertise in each area (Company B), much like Bijker's 'heterogeneous engineer'. In other words, environmental management programs that are highly specialized but disconnected may not be as effective as managing for sustainable development, which in our view is based on understanding, seeking out and exploiting strong interdependencies. We further caution that the complexities, ambiguities and idiosyncrasies of sustainable development make deductive approaches used in environmental management inadequate. Under such circumstances, Gavetti et al. (2005) recommend analogical reasoning, which is based on accumulated experience and alertness. While we are not suggesting that the discipline of environmental management is obsolete, we would suggest that it is becoming a role for middle managers or technicians, whereas the complexities and ambiguities of sustainable development will increasingly be the focus of senior operational and strategic managerial attention and frustration, as well as a rich area of academic research.

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Appendix A. Interview subjects by stakeholder category (number of subjects)

Energy sector. Senior executives, middle managers, environmental experts/LCA specialists, trade association officials (excluding 3 LCA workshops totaling 45 participants)	27
Agriculture sector. Senior executives, middle managers, environmental experts/LCA specialists, farmer association representatives, farmers (8 individual interviews, excluding 4 focus groups totaling 48 participants)	40
Forestry sector. Senior executives, middle managers, environmental experts/LCA specialists, trade association officials	9
Chemical sector. Senior executives, middle managers, environmental experts, LCA specialists	6
Miscellaneous manufacturing. Senior manager, LCA specialist	2
Government officials. Brazilian, Canadian and US senior officials	18
United Nations (*UN*) *officials*. Food & Agricultural Organization (FAO), UN Environmental Program, UN Division for Sustainable Development, Economic Commission for Latin America & Caribbean, UN Development Program	10
NGOs. Greenpeace Brazil, Greenpeace Canada, Greenpeace China, Greenpeace International, Sierra Club, Brazilian Institute for Consumer Defense, Project Tamar, Council for Canadians, Pembina Institute for Appropriate Development; Polo Sindical da Borborema (translates as Borborema Farmers Union), Esperanca and Lagoa Seca divisions	11
Community representatives	3
Academics	6
Consultants	3
Total	135

Appendix B. Interview questions

B.1. First round of data collection

Can you describe the role your organization plays in your sector? In your country? Elsewhere?
Who are the key stakeholders?
How important are they, and why?
How do they affect the industry?
How do they affect government policy?
Of these stakeholders, which affect your organization the most? How?
Which ones does your organization influence? How?
Are there many conflicting pressures from stakeholders? Can you give examples? How can they be resolved?
What are the main issues in your industry sector?
What role does sustainable development play in the industry?
What tools are applied to address sustainable development in your organization?
What are the key challenges of sustainable development in your company?

B.2. Second round of data collection

What are the key challenges of sustainable development innovation in your company? (Prompt for technological, commercial, organizational or social factors.)
If LCA is applied, what are the key variables considered in the analysis?
Are there any interactions among economic, social and environmental variables addressed on your SD program?
Do people responsible for environment, social and economic affairs in your company interact with each other?

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