A Strategy to Incorporate Social Factors into Engineering Education

Stelvia Matos and Olga Petrov

Abstract

As societal expectations have changed from narrowly focused environmental issues to broader sustainable development concerns, it is vital that future engineers graduate with an understanding of how social impacts may affect or may be affected by their decisions. Drawing on complexity theory and sustainability literature, this paper describes how engineering programs can incorporate a course that will enable graduating engineers to explore the interdependencies among technical, economic, environmental and social dimensions of sustainability. System's elements and interdependences are identified using modularity, a technique that applies deductive and inductive methods. Using the example of a sustainable lignin-based product we demonstrate how such methods can be demonstrated in class. We then discuss the implications for engineering teaching and propose an integrated sustainability analysis course that focuses on harnessing social factors within sustainability systems, by seeking them out and exploiting interdependencies. This will prepare future engineers to work on a more realistic scenario, and more broadly explore new ideas and possible solutions.

S. Matos (✉)
International Centre for Corporate Social Responsibility (ICCSR),
Nottingham University Business School, The University of Nottingham,
Jubilee Campus, Wollaton Road, Nottingham NG8 1BB, UK
e-mail: stelvia.matos@nottingham.ac.uk

O. Petrov
Chemical and Biological Engineering, University of British Columbia,
Vancouver, Canada
e-mail: Olga_Petrov@bcit.ca

O. Petrov
Environmental Engineering, British Columbia Institute of Technology,
Burnaby, Canada

W. Leal Filho and S. Nesbit (eds.), *New Developments in Engineering Education for Sustainable Development*, World Sustainability Series,
DOI 10.1007/978-3-319-32933-8_15

Keywords
Sustainable development · Social factors · Engineering education · Complexity theory · Curriculum

1 Introduction

While much has been discussed on incorporating environmental focused topics such as life cycle assessment, renewable energy, and waste minimization in engineering course materials, few changes have addressed the social component of sustainability (Tainter 2006; Davidson et al. 2010; Kohtala 2014). This implies that educators must revise courses and curricula so engineering graduates are prepared for the new challenges of sustainable engineering. A key barrier for such change is educator's difficulties to address the complex interdependence among the environmental, economic and societal dimensions of sustainability and to deal with qualitative data collection and analysis. Yet the need for change is urgent, as currently graduating engineers may not realize that isolated attempts to reduce environmental impacts may provide less than optimal solutions or even detrimental outcomes (Matos and Hall 2007).

This paper describes how an integrative analysis approach to sustainability can enable engineers to explore the interdependencies and to identify how social impacts may affect or may be affected by their decisions. We draw on complexity sciences and sustainability literature as a guide to understand the interactions and the different concepts involved in a sustainable system (Kauffman 1993; Innes and Booher 2000; Matos and Hall 2007).

We start by describing the similarities between complex systems and sustainability, as both involve a large number of elements or agents that connect and interact with each other in many different ways and are thus constantly changing and evolving (Kauffman 1993). As complexity theory also emphasizes the importance of searching for the interactions and sources of change among elements or agents that constitute a particular system (Mason 2009), we describe how modularization, a technique that has been applied to manage complexity, can be used as a framework for such searching process. Modularization consists of a process that identifies parameters, their role in the completion of a task and the degree of interdependences (Baldwin and Clark 2000). Parameters and interdependences are identified by deductive and inductive methods (Matos and Hall 2007). The former involves quantitative data, i.e. codified form of knowledge such environmental, costs and process design data. The latter involves qualitative information such as stakeholders' perception about the benefits of a technology and cultural values, which draw on social sciences methods for data collection, analysis and reliability. Using the example of a sustainable lignin-based product, we demonstrate how such methods are applied, providing educators with a practical example that can be used in class. Finally, we propose a sustainable analysis course that draws on this integrative approach and discuss the implications for engineering teaching.

In contrast to previous approaches to sustainability teaching that focused on exploring environmental and economic parameters disregarding cross integration with social factors, we propose harnessing social factors within a sustainability system, by seeking them out and exploiting interdependencies.

2 Sustainable Development and Complex Systems

Complexity theory has first been developed in the fields of physics, biology, chemistry and economics but it has been also applied in the field of social, organizational sciences and operations management (Thrift 1999). It deals with environments, organizations, or systems that have a very large number of elements or agents that interact to each other in many different ways (Kauffman 1993). These elements or agents may include atoms, molecules, human agents, institutions, corporations, etc. (Mason 2009). Complexity theory also suggests that it is the multiple interactions among the elements that are responsible for the phenomena, patterns, properties, and behaviors that characterize a particular field. Simon (1991) suggested that a complex system often takes the form of hierarchy by being composed of subsystems that, in turn, have their own subsystems, as molecules form cells, species form ecosystems and consumers and corporations form economies (Waldrop 1993).

Kauffman (1993) draws on the biological concept of fitness landscape to describe a complex system. In biology, fitness landscape is a distribution of possible genotypes (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 elements. The lower the number of interactions, the smoother the landscape (Fig. 1a) and the more straightforward is to find a combination of choices of elements that work, i.e. the highest peak. However, the more complex the system, the more rugged the landscape (Fig. 1b), and the more difficult is to make the right choices that lead to the

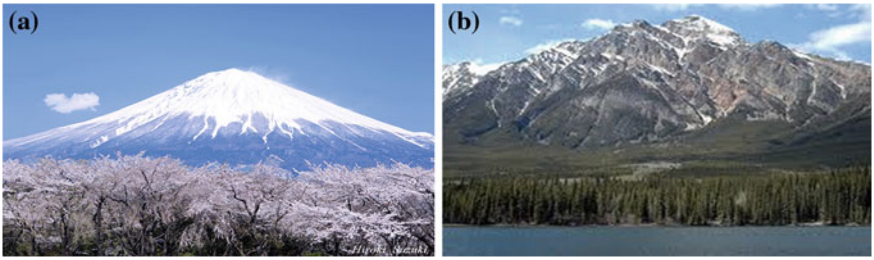

Fig. 1 **a** Smooth landscape or Fujiyama Mountain type—low number of interactions. *Source* http://sceneryseries.blogspot.co.uk/2008/12/fujiyama.html. **b** Rugged landscape or Rocky Mountains type—high number of interactions. *Source* https://www.flickr.com/photos/zinnie/305549202

highest peak because the number of possible solutions, or peaks, is large. In this case, the combination of choices of parameters that lead to the optimum solution may never be found. According to Kauffman (1993), in such situations it is better to satisfy rather than optimize avoiding complexity catastrophe, i.e. when considering too much interactive complexity hinders adaptation and stops the system's evolving process.

Similarly, sustainable systems are characterized by a large number of social, economic and environmental elements or agents that interact with each other (Matos and Hall 2007). A number of studies have examined the interactions of these elements. For example, in the case of transgenic technology, the interactions between environmental (potential impacts, risk), social factors (small farmers rights) and technology (research and development) had negative effects in the technology trajectory. Such effects included millions of dollars spent in legal actions and delays in technology diffusion (Chataway et al. 2004; Hall et al. 2014a). In the automobile industry, the 1950s Ford Edsel is a well known case of a technology launched as a stand-up product that led to millions of dollars lost in development, production and marketing (Dicke 2010). The very word Edsel became a symbol of commercial failure, which has been attributed to a number of factors including the lack of appropriate interactions between developers and consumers (Deutsch 1976). Another case is Iridium, a satellite-based mobile phone network launched in 1999 that promised to revolutionize communication systems by allowing calls to and from any point in the world. Yet the technology was a commercial failure, as developers did not consider consumers' end costs and willingness to carry a large and heavy phone around (McIntosh 1999).

Economic and environmental elements may include operating costs, pollutants, energy and water consumption, etc. Social elements include, NGO representatives, media, laws, regulations, etc. According to Matos and Hall (2007) sustainability is an inherently rugged landscape that requires coordination of social, environmental and economic systems. In addition, the inexistence of a single optimum requires agents to undertake a collaborative search approach, which can be accomplished by forming cross-functional teams, requiring tighter synchronization among their actions and establishing a common goal (Levinthal and Warglien 1999). This will encourage recombination of partial solutions, bringing together elements that were previously known but distant from one another. We speculate that had Ford Edsel and Iridium considered such cross-functional team approach during the technology development phases, they may have been able to adapt to consumers' expectations and needs at that time.

Levinthal and Warglien (1999) also suggest that communication among these agents is an important mechanism for igniting cooperation. Engineers' sound understanding of science and mathematics with the attention to economics, health and safety, and environmental impacts, give them the unique opportunity to play a crucial role in fostering collaboration among different teams.

3 Modularization Process Applied to Sustainability Analysis

Modular design structures are advocated as particularly useful when interdependencies between elements of the system is so large that integrated design efforts become almost impossible (Levinthal and Warglien 1999). The general idea of modularity is that a complex system can be managed by dividing it up into smaller pieces or modules where interdependence within elements of the same module is strengthened and independence across different modules is reduced. Strong interdependencies are easily identified (e.g. the links between raw material costs and product price within the economic module). Interdependencies across modules are harder to identify and to change (e.g. the links between food regulations and market prices across the social and economic modules). However, once the designers or technology developers acquire more knowledge about how the interdependency works, it becomes possible to choose a solution from a set of possibilities (Baldwin and Clark 2000). Drawing on Baldwin and Clark's Design Structure Matrix, Matos and Hall (2007) developed a framework to identify key elements and interdependencies in a sustainable system that includes the following steps:

1. List economic, technological, environmental and social elements. Ask "What elements would you consider?" Note that these elements do not have to be exclusively quantitative.
2. Seek for interdependences. Ask "If, there are any changes made in a element (e.g. change package material from plastic to cardboard), what other elements will also change?"
3. Identify task hierarchies. Ask "Whose decision do you need to know in order to make your decision?" For each element, identify all predecessor elements.
4. Identify uncertainties related to the technology or process under analysis. Ask:
    - Is it feasible from a scientific and engineering perspective?
    - Is it commercially viable?
    - Are there any potential environmental impacts that are unknown or require specific investigation?
    - Are there any potentially negative side effects on, or from, secondary stakeholders?

Note that interdependencies are found by identifying what elements change as a result of changes in other elements. The task hierarchy structure is also crucial to the understanding of interdependencies as it lists tasks and coordination links between agents. For example, if tasks A and B are interrelated but are performed by different agents, then these two agents must communicate with each other before making their final choices. In practice, the above framework calls for robust quantitative and qualitative data collection methods that ensure data accuracy and validity.

4 Deductive and Inductive Data Collection Approaches

As sustainability is inherently complex its design outcomes are never completely predictable. In order to manage these challenges, an integrated approach of search and adaptation needs to be considered. The first step is to list the system's design elements, and categorize the hierarchical relationships and interdependencies, i.e. applying deductive approach. This includes system information such as key inputs, yield, critical process conditions, e.g. temperature and pressure and design calculations such as process flow diagrams, mass and energy balances, equipment sizing, hazard and operability studies and economic analysis. These topics relate to the core body of engineering degree discipline and curricula. The second step involves inductive methods, which deals more with the tacit knowledge of designers about dependencies, and less with the codified, formal knowledge typically taught for engineers. We draw on social science methods to fill this gap and to develop a process of qualitative data collection and analysis (Fig. 2) (Glaser and Strauss 1967; Eisenhardt and Graebner 2007).

The process starts with secondary data sources from the academic literature, government and industry documents to identify the key issues related to the unit of analysis (e.g. a new process or technology) and both primary and secondary stakeholders involved in the value chain. Primary stakeholders are those with a direct interest in the technology, such as customers, shareholders, employees and suppliers and secondary stakeholders are those that can indirectly affect, or are affected by the technology, such as NGOs, social activists, media, etc. (Freeman 1984). Once preliminary issues and key stakeholders have been identified, a list of questions to be applied in interviews and/or focus groups is then developed and used to initiate the discussion, but not to constrain stakeholders' possibilities for raising relevant topics. The data collected allows for the identification of other relevant stakeholders and elements (Berg 1988). The interviews and/or focus group data is recorded and transcribed. Using computer-aided qualitative data analysis software, the transcriptions are coded into categories and subcategories of relevant elements. For example, the subcategories energy costs, raw material prices, profit margins, etc. form the category economic issues, much like the systems and related

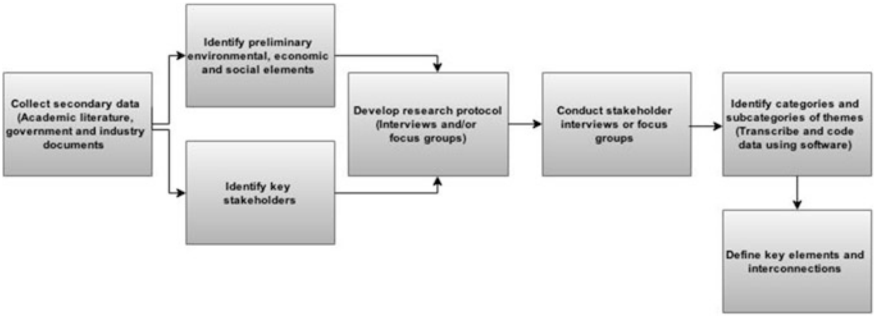

Fig. 2 Data collection and analysis process based on qualitative research methods

elements that describe a complex landscape. Note that interactions between categories are also identified during this process and can be coded under the theme "interconnections". For example, environmental performance may be affected by the choice of raw material of a certain product, which in turn may affect costs. Coding is usually performed in two rounds by different researchers for internal reliability, identification of gaps and interview follow-ups.

4.1 Identifying Key Variables and Interconnections: Sustainable Lignin-Based Product

An innovative bioprocess that produces vanillin from lignin has been developed by scientists at the University of British Columbia, Canada, as part of a broad research project aiming to explore new sustainable opportunities from lignocellulose-derived products. The new vanillin is produced via wheat straw fermentation using the lignin degrading bacteria *RHA045*, a mutant strain of the *Rhodococcus jostii* bacteria obtained through gene knockout technique (Sainsbury et al. 2013). Here we summarize a practical example of the application of the proposed integrated sustainability analysis, which can be used in class.

Deductive Data: Preliminary lab test results showed that vanillin can be produced from wheat straw with a maximum growth rate of 0.0139 min^{-1}, vanillin yield 96 mg/L, Monod constant $K_s = 0.0114$ g/L and optimal growth conditions of 30 °C and pH 7 (Sainsbury et al. 2013). Process design calculations based on these parameters included inoculation, fermentation, separation and extraction phases (Baldwin 2014). Key environmental issues identified during the design process included the need of an absorbent system to remove VOCs from the extraction column. In addition, it was recommended to keep the bacteria concentration in the reactors as low as possible to reduce carbon dioxide emissions from the fermentation process. Estimate inventory of key resources used and emissions generated in the production process are listed in Table 1.

Table 1 Inventory data for the production of vanillin via wheat straw fermentation

Material inputs	Amount	Unit/kg of vanillin
Molasses	17.77	kg
Ammonia	0.80	kg
Sulphuric acid	0.08	kg
Ethyl Acetate	0.08	kg
Water	9.45	m^3
Wheat straw	2.84	kg
Process electricity	404	kWh
Waste water	0.23	m^3
Carbon dioxide	13.72	kg

Inoculation, separation and extraction phases were included (Baldwin 2014)

Petroleum based vanillin prices range between \$12–15/kg, lignin based ranges around \$13.00–17.00, and natural vanillin between \$1200–4000 (Wong 2012). In the US, some high-end synthetic vanillin products can cost up to \$700/kg. Based on the inventory data collected during the process design calculations and the estimated costs of raw material, electricity and labour, the new vanillin has to be sold at a price of \$960/kg in order to break even the operating costs (Baldwin 2014). This is at least 60 times the market price for lignin-derived vanillin.

Inductive Data: Drawing on the methodological process depicted in Fig. 2, both secondary and primary data were collected and analysed, leading to the identification of the key social elements related to the proposed new vanillin. First, the high variance in price between synthetic vanillin and natural vanillin noted above draws the attention to the natural foods market as a potential target for this product (Hall et al. 2014b). However, the definition of 'natural' and related regulatory labels varies between countries. For example, a Norwegian company produces a specific type of vanillin that meets the EU requirements for "nature-identical" and it is thus sold at a higher price than regular lignin-based vanillin (Wong 2012). For the new vanillin, the Canadian Food Inspection Agency (CFIA) indicated it does not qualify as natural, although additional technical information may lead to approval for a "natural flavour" label:

> The production of vanillin from wheat straw using bacteria fermentation would not be considered natural as it utilizes chemicals in the process. […] Under the "Nature, Natural" section of the Guide to Food Labelling and Advertising, there is a small section regarding "flavour descriptors". The information in that section could still apply to your product." (CFIA Chemistry Specialist)

The questions here are whether the process can be changed to exploit the lucrative 'natural market', whether it is possible to induce regulatory reform, or if it is more feasible to exploit the technology elsewhere, where the process meets 'natural' regulatory criteria (Hall et al. 2014b).

There are contrasting views about genetic engineering technology from different stakeholders. From one side, scientists expect consumer acceptance regarding the knockout technique used in vanillin preparation to be straightforward. One scientist stated that "… *there should be no issue because bacterial and other microbial strains have been used for many centuries in food preparation, and so this is something that is still done today in many different ways; for example, preparation of soy sauce, brewing of beer, things like that*." On the other side, an NGO protest against any kind of production process that does not come from the natural beans states that:

> ETC (Erosion, Technology and Concentration) Group and Friends of the Earth are launching a public design and branding competition to shine a spotlight on synthetic biology (extreme genetic engineering) in our food. Use your creativity to help us expose the very un-natural new ingredient coming to a confection near you, and what it means for vanilla farmers." (ECT 2014).

Key Interactions: Although the new vanillin production process has been shown to be technically feasible, the data indicated that there might be opportunities of developing vanillin for the more lucrative natural market. Such economical issue interacts with the technology aspect of the proposed process, as the developers need to consider making changes in the process so it falls within the definition of natural. Although changing the production process and maintaining costs below $700/kg remain challenging, the lucrative natural market niche provides a useful value proposition as justification to proceed with developing the technology (Hall et al. 2014a). Note that regulatory definitions for food additives and "natural" market trends are highly complicated and specialized business issues are beyond the radar of engineering curricula. Nevertheless, by acquiring knowledge about how inter-dependency works, it becomes possible to identify what set of skills need to be sought out in order to bring together the required elements of a possible solution and then adapt.

Regarding NGO's perception of the technology, it is difficult to predict whether there will be protests and if they will have any effect on the development and application of the vanillin technology. However, this shows the importance of the technology developers and engineers to adapt by being aware of the different views in case there are opportunities to address stakeholders' concerns about the technology. For example, it may be helpful to clarify that the technology involves knockout gene technique to avoid any confusion with the GMO technology, which has been notorious for generation negative reaction from the public.

5 Integrated Sustainability Analysis Course

We propose a course that integrates social elements into the environmental and economic analysis of sustainability for engineering (Table 2). This course will enable graduating engineers to identify and examine key social issues related to engineering operations, first by learning relevant methods to collect and analyse qualitative data and then by exploring the interconnections between sustainability dimensions.

The course starts with an overview of key concepts and the description of sustainable systems through the lenses of complexity theory and landscape theory. The point here is to show that, similar to complex systems, sustainability requires an integrated analysis of its core elements, in this case, environmental, economic and social factors. In the beginning of the course, the graduating engineers are encourage to connect with the university's science and engineering faculties and identify a potential innovation that they can use as case study throughout the course. Then modularity is described as a useful technique applied to manage complexity systems, helping to identify key environmental, economic and social elements and interconnections related to that particular potential innovation. Next, a review of deductive methods for environmental and economic data collection and analysis is

Table 2 Integrated sustainability analysis course contents

Part 1: Introduction
- Course description and objectives
- Course project description, selection of themes (case studies) and respective groups

Part 2: Introduction to complexity theory and fitness landscape
- Definition, key characteristics and related concepts

Part 3: Sustainable development as a complex adaptive system
- The links between complexity theory and sustainable systems

Part 4: Search and adaptation processes: identifying elements and interconnections
- Modularity approach, design and task structure matrices of interactions

Part 5: Deductive approaches: When to apply what quantitative analysis methods?
- Environmental (LCA, risk assessment, etc.)
- Economic (cost estimates, market prices)

Part 6: Integrate frameworks and content of course-to-date into the case studies

Part 7: Inductive approaches: social sciences qualitative data collection and analysis methods
- Design and site selection
- Data gathering
  - Secondary data and desk research
  - Primary data collection methods: interviews, focus groups, surveys
- Data analysis
  - Mapping: identify and describe critical elements
  - Identify linkages between elements
  - Coding process
  - Textual analysis software
  - Overlapping data collection and analysis
  - Measuring data validity and demonstrating reliability

Part 8: Integrate inductive approaches into the case studies

Part 9: Course project wrap up
- Demonstration of integrative analysis using both deductive and inductive methods
- Identification of key environmental, economic and social parameters and interdependencies

presented with a focus on key differences, advantages and disadvantages. Next, an in depth description of inductive methods is performed, including data design collection and analysis, issues with reliability and data validity. The course contents are then integrated into the case studies projects where the graduating engineers are expected to demonstrate their ability to perform a simplified integrated sustainability analysis using the approaches discussed in class.

6 Conclusions

Integrating social factors into sustainability analysis remains a gap in the engineering curricula as it usually focuses on environmental and economic aspects of a new product or process. However, as sustainability is essentially a complex system, its core elements, i.e. environmental, economic and social factors, interact with each other, and failing to consider this interaction may lead to counter-productive or unsustainable decisions. We suggest that implementing a course that draws on the key concepts of complexity theory can fulfill this gap.

Our contributions to the sustainability education discussion are two fold. First, we propose that the analysis of social impacts needs to be taught as an integrative component of the environmental and economic analysis of sustainability. Social factors, and their potential impact on and from engineering decisions, have not been fully explored in engineering courses. Second, we contribute by presenting a specific/practical analytical process of qualitative data that will allow graduating engineers to identify and analyze social factors.

Search process include both deductive and inductive approaches, the latter addressed by applying social sciences data collection and analysis methods. We suggest that by exploring search and adaptation processes (i.e. assuming a rugged landscape) engineers will have opportunities to identify effective solutions that would otherwise be missed under a 'smooth landscape' approach.

Acknowledgements Funding for this research was provided by Genome British Columbia and Genome Canada. The authors would like to thank those who participated in our research our co-principal investigator Dr. Jeremy Hall and collaborators Dr. Vern Bachor and Dr. Robin Downey.

References

Baldwin, C. Y., & Clark, K. B. (2000). *Design rules: The power of modularity*. Vol. 1, MIT press.

Baldwin, S. (2014). An Innovative Approach to Vanillin Production via Lignin Degradation using Rhodococcus jostii RHA045. Course Project Report. Department of Chemical and Biochemical Engineering. University of British Columbia, Vancouver, Canada.

Berg, S. (1988). Snowball sampling. In S. Kotz & N. L Johnson (Eds.), *Encyclopedia of statistical sciences* 8th edition.

Chataway, J., Tait, J., & Wield, D. (2004). Understanding company R&D strategies in agro-biotechnology: Trajectories and blind spots. *Research Policy, 33*(6-7), 1041–1057.

Davidson, C. I., Hendrickson, C. T., Matthews, H. S., Bridges, M. W., Allen, D. T., Murphy, C. F., et al. (2010). Preparing future engineers for challenges of the 21st century: Sustainable engineering. *Journal of Cleaner Production, 18*(7), 698–701.

Deutsch, J. G. (1976). *Selling the people's Cadillac: The Edsel and corporate responsibility*. Yale University Press.

Dicke, T. (2010). The Edsel: Forty years as a symbol of failure. *Journal of Popular Culture, 43*(3), 486–502.

ECT Group (2014). "Competition Launch to 'Brand' Synthetic Biology Vanilla". http://www.etcgroup.org/content/competition-launch-'brand'-synthetic-biology-vanilla. Assessed 16 Nov 2014.

Eisenhardt, K. M., & Graebner, M. E. (2007). Theory building from cases: Opportunities and challenges. *Academy of Management Journal, 50*, 25–32.

Freeman, R. (1984). *Strategic management: A stakeholder approach*. Boston: Pitman.

Glaser, B. G., & Strauss, A. L. (1967). *The discovery of grounded theory: Strategies for qualitative research*. Chicago, IL: Aldine.

Hall, J., Bachor, V., & Matos, S. (2014a). Developing and diffusing new technologies: Strategies for legitimization. *California Management Review, 56*(3), 98–117.

Hall, J., Matos, S., Bachor, V., & Downey, R. (2014b). Commercializing University Research in Diverse Settings: Moving Beyond Standardized Intellectual Property Management, *Research-Technology Management, 57*(5), 26–34.

Innes, J. I., & Booher, D. E. (2000). Indicators for sustainable communities: A strategy building on complexity theory and distributed intelligence. *Planning Theory & Practice, 1*(2), 173–186.

Kauffman, S. A. (1993). *The Origins of Order: Self-organization and selection in evolution*. Oxford university press.

Kohtala, C. (2014). Addressing sustainability in research on distributed production: An integrated literature review. *Journal of Cleaner Production* (in press).

Levinthal, D. A., & Warglien, M. (1999). Landscape design: Designing for local action in complex worlds. *Organization Science, 10*(3), 342–357.

Mason, M. (2009). Making educational development and change sustainable: Insights from complexity theory. *International Journal of Educational Development 29*(2), 117–24.

Matos, S., & Hall, J. (2007). Integrating sustainable development in the supply chain: The case of life cycle assessment in oil and gas and agricultural biotechnology. *Journal of Operations Management, 25*(6), 1083–1102.

McIntosh, B. (1999). Down to earth reasons for Iridium failure. Available at: http://www.independent.co.uk/news/business/down-to-earth-reasons-for-iridium-failure-1113638.html.

Sainsbury, P. D., Hardiman, E. M., Ahmad, M., Otani, H., Seghezzi, N., Eltis, L. D., & Bugg, T. (2013). Breaking down lignin to high-value chemicals: The conversion of lignocellulose to vanillin in a gene deletion mutant of rhodococcus jostii RHA1. *ACS Chemical Biology, 8*(10), 2151–2156.

Simon, H. A. (1991). *The architecture of complexity*. US: Springer.

Tainter, J. A. (2006). Social complexity and sustainability. *Ecological Complexity, 3*(2), 91–103.

Thrift, N. (1999). The place of complexity. *Theory, Culture & Society, 16*(3), 31–69.

Waldrop, M. M. (1993). *Complexity: The emerging science at the edge of order and chaos*. Simon and Schuster.

Wong, J. T. (2012). Technological, commercial, organizational, and social uncertainties of a novel process for vanillin production from lignin.