SUSTAINABLE CONSUMPTION AS A CONSTRAINT TO SUSTAINABLE PRODUCTION

ABSTRACT

This paper trials the use of q-analysis as a data analysis method to investigate what are the constraints to sustainability for the UK offshore wind industry. q-analysis is used to remove the indeterminacy of an interpretive case study methodology when trying to identify bottlenecks to sustainability. In the sample case study used in this paper, factors exogenous to the industry and its supply chains are shown to be the bottleneck, revealing a case where a lack of interest in sustainable consumption is the constraint to achieving sustainable production.

Key words: offshore wind, sustainability, decoupling point, q-analysis.

INTRODUCTION

Much of operations and technology management research and practice has relied on separation and decoupling principles, i.e. the notion that consumption and production are separate affairs. For example, in service science, gains in efficiency have been achieved by applying contact theory to differentiate the sub-systems that require customer contact from those that do not. This results in the definition of a back-office systems that can be managed in the same way than a manufacturing system, i.e. a system where customers cannot interfere with performance. In the manufacturing sector, the traditional decoupling point is the point that delineates the point where material flows/supply chains switch from working with make-to-order to make-to stock systems (Van Donk, 2001; Olagher, 2010; 2003). This is important in terms of achieving mass customisation benefits in the upstream supply chain (Rudberg and Wikner, 2007) and economies of scale in the downstream supply chain. In technology management, the decoupling effect can be severe as technologies may be developed in contexts where markets and applications are unclear/unknown.

The impact of the decoupling point is that operations systems are often disconnected from real demand conditions, which leads to well documented and researched issues such as the bullwhip effect. As a result, operations and technology managers have developed their own set of techniques to make sure that their disconnected-by-design systems remains connected. Such 'coupling' efforts are done in the information domain, as the material flow decoupling point has an information decoupling point counterpart in the demand chain (Mason-Jones and Towill, 1999; Giesberts and Tang, 1992).

Although the material decoupling point addresses a genuine economic reality, there is something inherently paradoxical in the simultaneous deployment of decoupling and coupling mechanisms in technology and operations management when the decoupling concept is considered more broadly. Push/pull theory (Zmud, 1984) proposes that "*innovation is most likely to occur when a need and a means to resolve that need are simultaneously recognised*". Zmud's statement seems very relevant in the modern context of sustainability. The purpose of the paper is to investigate if it is possible to design sustainable supply chains when production concerns are decoupled from consumption concerns? As sustainability is concerned with the planetary impact of technologies and operations systems, working with decoupled systems seems counter-intuitive. A simple illustration of the challenge of decoupling is as follows: what is the value of intermittent green energy generation technologies, such as wind power, that require expensive and polluting heavy oil back-up generators to supply power to customers in the absence of wind? This is an argument often used to argue that wind power is not sustainable. To claim sustainability, the customers would have to accept the requirement of coupling production and consumption and commit to use wind power when it is available, and to refrain from using energy when it is not. It is generally agreed that this is an unlikely scenario.

THEORY

This paper explores this paradox from the sustainable supply chain behavioural search theory proposed by Leseure and Alexander (2017). The purpose of this paper is to investigate methodological challenges to the validation of this theoretical perspective. The purpose of this section is solely to summarise this theoretical perspective, and the methodological challenges are discussed in the following section.

There is an extensive literature that criticise corporate claims to sustainability. It is argued that claims to sustainability are too simplistic (e.g. Gray, 2010) and are hypocritical organisational facades (Cho et al., 2015). Organisations that claim that their offsetting programmes are proof of sustainability provide examples of such facades, that mask the purposeful postponements of investing in truly sustainable operations (Shevchenko et al., 2016). The problem is compounded by the fact that there is no generally agreed-upon definition of sustainability (Gray, 2010; Owen, 2003) and that even when a widely used definition of sustainability is used, such as the WCED definition (WCED,1997), its implementation remains equivocal, i.e. the trade-offs between the three dimensions of the triple bottom line remain implicit.

Like many authors (e.g. Gray, 2010), Leseure and Alexander (2017) argue that it is difficult, if not impractical, to account for sustainability at a corporate level and that it is only by observing entire supply chains that sustainability of practices/technologies can be assessed. This argument can easily be extended to industrial ecosystems made up of several supply chains. Therefore, Leseure and Alexander (2017) investigate supply chains not as a traditional network of suppliers and buyers or as multi-echelon inventory systems but from the perspective of Brown and Duguid's (1991) communities of practice (CoP). Brown and Duguid argue that learning and innovation and new ways of working are discovered and shaped in communities of practice rather than within the less exploratory and more formal settings of the corporation. It is only through the concerted and collaborative actions of members of CoPs that new technologies and practices are designed and adopted so that whole supply chains become more sustainable.

The fact that the meaning of sustainability is vague and debated means that management efforts to present their organisations as being sustainable should not be analysed as actual claims but as an acknowledgment of their organisations partaking in a search process, as defined by the behavioural theory of the firm (Cyert and March, 1963). As predicted by the behavioural theory of the firm, it should be excepted that opposing coalitions will form. It is interesting for example to compare Japanese manufacturers' abandonment of diesel engines in their domestic fleets of passenger vehicles in the late 1990s with the intense R&D efforts to develop low consumption low pollution diesel engines by European manufacturers. These radically opposed search directions (abandon vs. invest in 'green' diesel) illustrate different coalitions within an industry. A significant controversy of the 'green diesel' search was the systematic failure of the turbochargers in HDi engines co-developed by Ford and Citroen and commercialised in a Ford-Citroen-Peugeot-Mazda-Mini-Volvo coalition.

In the context of a search process, it becomes meaningless to assess performance as the attainment of targets. An assessment of sustainable performance instead requires an assessment of learning and of the suitability of the search direction. In technical terms, is the search progressing toward a global optimum or is it 'stuck' at a local optimum? Given the Volkswagen diesel car emissions scandal, the previously mentioned systematic failure of diesel engines, and the current commitment of several European governments to eradicate diesel engines in passenger vehicles, it would appear that the search for cleaner cheaper diesel engines might not have been the best direction of search!

If one accepts that assessing sustainability is an assessment of how well the search is progressing, this implies that supply chains can only become truly sustainable if we understand what their constraints to sustainability are. If a supply chain CoP persists in a seemingly doomed direction of search, this is a case of escalation of commitment to a course of action (Staw, 1981) that raises questions about the rationality and motivation of the CoP members.

Leseure and Alexander (2017) propose that CoP members in their annual sustainability performance assessments should concentrate on the identification of what they perceive to be the constraints to becoming sustainable. To this end, they customise Siemsen's et al. (2008) constraining factor version of the Motivation-Opportunity-Ability (MOA) model. The MOA framework predicts the performance of a task (either individual or collective) based on individuals' motivation (M) and ability (A) to perform this task. For example, a skilled but poorly motivated student may not do well in an exam. The opportunity variable was added to the MOA framework to capture the impact of exogenous 'opportunity' factors on performance (e.g. exam room conditions). The constraining factor model version of the MOA framework states that to improve behaviour/performance, one should concentrate on the constraining factor (M, O, or A), consistently with the theory of constraints (Goldratt and Cox, 1984).

Through two case studies, Leseure and Alexander (2017) find that opportunity, i.e. factors exogenous to the supply chain, are often the constraints to becoming more sustainable. This provides a contrasting position to the literature that argues that motivation is the constraint to sustainability (e.g. the use of rhetoric to avoid investments in sustainability, Ihlen, 2009; delaying investment in sustainability as a rational decision, Shevchenko et al., 2016).

The proposition that opportunity may be the constraining factor to sustainability in several industries is a significant issue. If indeed what stops members of supply chain CoPs to implement truly sustainable practices are exogenous, consumption-related issues, then it would mean that the main constraint to sustainable production is non-sustainable consumption, i.e. a sustainable technology push may fail simply because customers are not interested in it.

METHODOLOGY

Methodological Challenge

Although the above conclusion is conceptually appealing, there are several reasons why it is difficult to demonstrate it empirically. The MOA model and its constraining factors version has been used successfully in positivist survey research using individuals as the unit of analysis. In the theoretical framework described above, the unit of analysis are the different coalitions of individuals that adopt different directions of search. Although supply chain research increasingly uses unique research designs (e.g. surveying both buyers and sellers in dyads), the idea of identifying and then surveying members of different coalitions in cross-industry, inter-organisational, inter-supply chain networks raise many cost and feasibility issues, such as for example defining whether or not a CoP search requires actual meetings, one to one conversations or can be conceptualised as a search process taking place over a more distributed and fragmented set of simultaneously competing and collaborating networks.

Furthermore, the nature of a search process is to be messy, iterative and to be prone to failure. If one uses the example of the probe and learn search process (Lynn et al., 1996) many local directions of search will be considered and explored before a branch is accepted to be a 'dead end' and before a CoP re-directs its search in a globally more promising direction. This means that at a micro-scale level of research, i.e. one where the behaviour of the individual search actors is observed, a researcher will be facing considerable 'local noise' which may not be a representative illustration of the real constraints to becoming more sustainable.

Research about the constraints to sustainability is research about collective work (by the coalitions within the supply-chain based communities of practice), the directions of search that they explore, and what constrains these searches. This is a more macro-level phenomenon that is akin to case case study research (e.g. the case studies used by Lynn et al. to research the probe and learn search process, 1996) or policy evaluation. At an early stage of research into a phenomenon, such research is often based on interpretive methodologies. Although they permit and facilitate exploration of a phenomenon, they offer little guarantee in terms of the general quality of a conclusion.

If (non sustainable) consumption is truly a constraint to sustainable production, there are important policy and education implications. For example, it is questionable to penalise producers for not being sustainable when the main constraint to sustainability is the customer's behaviour. The problem is not so much the number of case studies that can be performed but the reproducibility of findings from a case study. Leseure and Alexander (2017) used two case studies: the UK offshore wind sector and the heavy construction sector. Their conclusions would have little validity if different researchers looking at the same issues would interpret the cases differently and reach different conclusions.

Methodological Framework

The purpose of this paper is to develop a method of data analysis to apply the constraining factor version of the MOA framework in a qualitative research context where the unit of analysis are coalitions within supply chain communities of practices. Whereas Leseure and Alexander’s (2017) work is based on an interpretive case study methodology, the purpose of this paper is to revisit one of the cases from a positivist case study methodology, where, consistently with Yin's (1994) original treatment, more importance is given to the definition of the variables, their instrumentalisation, and the method of data analysis.

The first research variable represents the different directions of search pursued by a supply chain CoP. These form a set $\{S_i\}_{i=1..n}$ of *n* possible search programmes. Each search direction S_i represents a local search direction, and each is associated with a coalition of individuals investing time and resources in the search. Within a supply chain community, an individual can be a member of several search coalitions, but their commitment to each will vary.

The second research variable is the set $\{C_i\}_{i=\{i=1...m\}}$ of *m* constraints faced during a search process. The MOA framework suggests that these constraints can be classified according to 3 types, M, O, or A. A search can be constrained by motivation, which means that coalitions members invest little time and resources into the search or refuse to participate in the search efforts. Some may even actively criticise the search as a waste of corporate resources. A search can be constrained by ability, i.e. coalitions of members do not have the skills and knowledge to move forward. Finally, a search can be constrained by opportunity, i.e. factors that are exogenous to the supply chain community of practice.

The purpose of case study research investigating constraints to supply chain sustainability is to research the relationship between the sets of search directions $\{S_i\}$ and constraints $\{C_i\}$, i.e. to reveal structural patterns between these two sets. This can be described as an algebraic topology problem, and this paper uses Atkins' (1974) q-analysis formalism to derive a duplicable method of data analysis and pattern identification.

The purpose of data analysis should be to document the relationship λ between the search direction S_i and the constraints C_i. A search direction and a constraint are connected by λ if there is evidence showing that a constraint is affecting search efforts. With q-analysis, each direction of search is a k-dimensional simplex defined by the number of constraints that it faces.

For example, $S_1 = \langle C_1\ C_3\ C_6 \rangle$ indicates that the search S_1 is a 2-dimensional simplex defined by its three constraints (a search subject to only 1 constraint is defined as being of nil dimension). More generally, the colllection $K_S(C, \lambda)$ of simplices (S_i) is a simplicial complex. It is possible to perform a q-analysis of this simplicial complex by looking for structural commonalities between each search direction. The simplices S_i and S_j are q-connected if there is one chain of connections of length *h* and of dimension *q* between them (i.e. sharing directly or indirectly q+1 constraints). At each dimensional level, the search directions S_i form Q_i different q-connected subsets. The relationship λ is characterised by a structure vector $Q = (Q_n, Q_{n-1}, ..., Q_0)$. The norm of this vector is a measure of the complexity of the structure. This means that it is possible through this measure to compare the structural complexity of achieving sustainability for different industries/case studies.

$$Ecc_{S_i} = \frac{q^+ - q^-}{1 + q^+}$$

The above equation defines the eccentricity of a simplex, i.e. the unusual or non-conformist nature of a simplex within a set. q^+ is the top-q or dimension of the simplex whereas the bottom-q (q^-) is the largest q-value at which this simplex is connected to a distinct simplex.

Data sources and data collection

The data used to illustrate the methodology described above is based on qualitative field research. The author was involved in three successive applied research projects about the fabrication supply chain associated with the UK offshore wind sector. Although the projects were not about the sustainability of this sector but about the development of a UK-based equipment supply chain, the projects required interactions with the sector in terms of estimating future market size and of preparing a scenario analysis of future growth. These aspects of the projects required an immersive experience with the sector. This included the attendance of industry events (such as the annual *All Energy Conference*), a survey of industry experts, and many interviews and workshops with a diversity of stakeholders. The analysis presented below is based on the data that was collected in 4 years of involvement with the offshore wind sector through these 3 projects.

CASE STUDY

The UK Offshore Wind Industry

Many countries have embraced the sustainability agenda in their energy sector, or more accurately, have joined a 'greener power' coalition for more sustainable energy supply chains. This coalition is motivated by a collective belief in the causality between carbon emissions and global warming, and search for ways to reduce emissions in power generation. Greener power is also worth pursuing from a social sustainability standpoint as it has the potential to improve energy security by reducing dependency on fossil fuels sources that are associated with complex and controversial geopolitical issues, including many armed conflicts. The ability to reduce energy cost is also a key determinant of macro-economic performance. It is difficult to think of an industry that better epitomises the stakes of true sustainability!

Wind power is a popular solution in countries' attempt to improve the sustainability of their electricity supply chains. When countries such as Denmark and Germany heavily invested in R&D in the 1980/90s, the United Kingdom dismissed the sector as uneconomical, at a point in time when UK electricity was mostly generated by coal. Times have changed, and the UK has completed a full policy turnaround. Onshore wind, the only renewable energy technology that currently competes cost-wise with traditional fossil fuels, is a minor part of the UK's energy portfolio though. This can be explained by the fact that the UK was a late mover compared with other European countries and by the fact that onshore wind farms have been met with unyielding social opposition. Only 1 in 6 proposed wind farms ever go through the consenting stage, and the UK Department and Energy and Climate Change (DECC) has announced that such projects will not be considered in the future. Instead, much of the focus has turned to offshore wind farms. At the time of writing of this paper, the UK boasts the largest commercial wind farm in operation in the world, London Array, but also the largest total commercial installed offshore wind capacity.

Whether or not these investments are truly sustainable has been a source of ongoing debates. Key issues are the increased cost of electricity and the challenge of managing intermittent power supply sources. Historically, electricity from offshore wind has been very expensive, sometimes twice more than the base market rate. The price difference has been absorbed through a variety of subsidising mechanisms. The cost issue has been worsened by the fact that the cost of building offshore wind farms has increased steadily in the last decade, but experts agree that it should now stabilise and start to decrease, 2017 being seen as the turning point for the industry. The second controversy is that wind farms only produce electricity when there is wind and do so in an unsteady fashion. As it is currently impossible to store energy commercially (the UK does not have a huge potential for pumped hydro storage, the only currently viable solution), wind farms, if used for base power generation, require backup generators. These are not only expensive to operate but polluting, defeating the very purpose of using wind energy in the first place. Leseure (2016a) explains that the UK is currently circumventing this problem as offshore wind farms are not built to replace fossil fuels power plants but to operate in parallel with them. When it is windy, the output of traditional sources is reduced accordingly. This means that the current practice is to use an expensive source of energy that reduces the utilisation of the cheap source, a practice which increases the cost of the cheap source. This does not seem to be a very sustainable arrangement. As the UK is set to decommission its remaining coal power plants (representing 30% of its total capacity in 2015) it is not clear what the electricity supply chain of the future will be like. This illustrates the case of an entire sector moving towards sustainability, without any stakeholder knowing precisely what the future system configuration will be.

In this case study, the community of practice are individuals collectively involved in this energy transition. It is an extremely dispersed community due to the complexity of the underlying design problem, the variety of participating organisations, but also the number of specialist disciplines that are involved. Key stakeholders are DECC, a number of government-affiliated networks and bodies promoting and stimulating the sector (e.g. the Renewable Catapult), the National Grid, regulators, energy firms, and large-scale technology providers. These interact with a multitude of smaller stakeholders: research centres and centres, universities, local government, and businesses. Organisationally speaking, this community of practice is vibrant with exchange with large conferences and trade fairs (e.g. the *All Energy Conference*) taking place nearly every month of the year.

Considering the buzz that is readily observed in all these events, the intensity and duration of strategic debates that takes place between the stakeholders, the number of responses to public consultations, the quantity of competing bids for research funds, it is easy to conclude that the motivation of this community is high and therefore very unlikely to be the constraining factor to sustainability.

Ability is a different story. The amount of intellectual capital forming this community is impressive, yet its ability to transcend specialisation is a question mark. It is interesting to note that the main ability challenge is a challenge of co-ordination and integration, i.e. a typical operations management challenge. Different stakeholders are trying to direct searches in a vast number of directions. Examples of search directions cover the full electricity supply chain from generation to consumption: lowering technology costs, the development of floating wind turbines, alternatives technologies such as tidal and wave power, the development of the European super-grid, energy storage, smart dynamic grids, and smart consumption. The ability to innovate and propose solutions in each of these directions is very high but coalitions do exist. For example, the wind coalition tends to consider wave energy as an unproven concept and as too expensive. The wind coalition often views floating wind as an unlikely technology, much to the dismay of the floating wind coalition. Although there are some obvious synergies between some of these search directions (e.g. between lowering the cost of offshore wind and energy storage), the synergies can only be achieved through co-ordinated actions. For example, smart homes coupled with a market incentive to encourage consumers to increase consumption at the right time (e.g. a washing machine offering a discount to take advantage of wind energy surplus) could reduce the problem of intermittence, but neither technology has any value if the transmission grid is not flexible enough to allow these dynamic adjustments to supply and demand. Leseure (2016a) equates this challenge with a sales and operations planning (SOP) problem and concludes that the current design of the UK transmission system and market mechanisms prevent any form of SOP. In December 2015, the UK EPSRC has released a call for tender for research project scoping 'whole energy systems', in recognition of this challenge of integrating abilities. Whether or not the scoping studies and their subsequent projects will be enough to address the challenge remains to be seen.

Opportunity is an unusual dimension to consider in technology and operations management research, and amounts to investigating how exogenous factors, such as consumer behaviour, and more generally society's behaviour, affect the performance of the supply chain. Leseure (2016b) explains that this omission is counter-intuitive as "*processes of social acceptance shape supply chain networks, influence location decisions, and define the underlying values from which supply chain design principles are formulated*". As mentioned above, 6 out 10 onshore wind farms have historically been rejected. An analysis of UK planning data shows that the rate of acceptance of UK offshore wind farms is only 50%. This is surprising as opinions polls consistently suggest that up to 77% of the UK public is in favour of renewable energy. This discrepancy is well known as the social gap and is described and analysed in detail along with its constituent NIMBY effect by Bell et al. (2005). Bell et al. (2005) describes the current consenting process with the following sequences: experts (from the community of practice) determine where a wind farm could be built; developers announce the decision to build. This typically raises concerns from local residents and developers are left to defend their decisions. Leseure (2016b) describes the Navitus Bay case study, a project larger than the existing London Array wind farm, which was rejected, amongst a very long list of reasons, for fears that its landscape impact would negatively affect the local tourism industry. There is ample academic evidence that such negative impacts have never been experienced and that wind farms can have a positive impact on tourism. Typically, developers spend 0.5% of their project capital expenditure on managing social acceptance but have already committed 4.3% of their budget by the time interaction with the public begins. If we consider planned projects only in the South East of the UK in the next 5 years, this means that lack of social acceptance will cost developers £1.8bn in lost development project expenses.

The government does not currently seem overly concerned with the issue of social acceptability and more with the issue of ability in terms of technology, R&D, and encouraging the associated manufacturing industry (e.g. turbine and associated component manufacturing). Although such manufacturing jobs are indeed desirable for an economy, it could be argued that this traditional form of industrial policy risks, like most forms of local content requirements, to increase technology cost and therefore to exacerbate the issue of public resistance as the technology is perceived to be too expensive.

Although the UK currently hosts the largest offshore wind farm park in the world, the actual installed capacity, when compared with UK demand and overall capacity, means that this park is a local search, a mere first step, towards a genuine sustainable supply chain. It is difficult to conclude with certainty, on the basis of this discussion above, whether ability or opportunity is the constraint to continuing and intensifying this search. This means that CoP members and policy makers are in the same position as manufacturing managers before the theory of constraint (Goldratt and Cox, 1984), i.e. in a position where they must invest to resolve a number of issues, without knowing what the real bottleneck to improvement is.

Case Analysis

This section applies the q-analysis method to investigate further the constraints to sustainability that the UK offshore wind power sector is facing. Instead of concluding that it is unclear whether ability or opportunity is the constraint, q-analysis is used to reveal the more complex picture between all constraints, as shown in Table 1. The coding of Table 1 is supported by the evidence provided in the appendices 1, 2, and 3. When considering the sustainability of this sector, i.e. whether offshore wind will be part of the future energy portfolio of the UK, 8 constraints were identified. The selection of these 8 constraints is based on the above case study narrative, the applied research projects that have informed this project, and a systematic review of offshore wind conference proceedings.

	Constraints								
	A	A	A	O	O	O	M	M	
	Sites	Transmiss	CoP know	Local acce	Political (r	Customer	Finance	R&D	
Searches	C1	C2	C3	C4	C5	C6	C7	C8	
Low LCOE									
Derisk									
S1.Project finance				1	1		1		**3**
S2.Cable reliability			1				1		**2**
Technology improvements									
S3.Equipment scale	1			1					**2**
S4.Hardware and site design innovation								1	**1**
S5. Supply chain			1		1			1	**3**
Alternatives									
S6. Floating wind			1	1				1	**3**
O&M improvements									
S7. Vessels					1				**1**
S8.Predictive maintenance								1	**1**
S9. Utilisation (load factors)		1	1	1	1	1		1	**6**
Steady, level supply									
S10. Wind with storage		1		1			1		**3**
S11.Wind-wave, other mixes		1		1			1		**3**
S12.Deep offshore		1							**1**
S13.Stand alone wind	1	1	1	1	1				**5**
Constraints Dimensions	***2***	***5***	***5***	***7***	***5***	***1***	***4***	***5***	

Table 1. Q-Analysis of the Constraints to Sustainability in the Offshore Wind Sector

The 8 constraints are:

- C1-Sites (ability): this refers to the availability of sites for building and operating offshore wind farms in terms of weather conditions, foundations requirements, and grid connection.
- C2-Transmission (ability): this refers to the ability of the national grid to handle power generated by offshore wind farms.
- C3-Knowledge (ability): this refers to the R&D ability of members of the supply chain CoP. Can they design effective technological solutions to address today's challenges?
- C4-Local acceptance (opportunity): this refers to whether or not local residents and other external stakeholders welcome offshore wind farms.

- C5-Political acceptance (opportunity): this refers to the amount of support that the industry is likely to receive at a national level. In the UK, the offshore wind sector has become a political issue with some parties opposing it and others encouraging its development.
- C6-Customer preferences (opportunity): this refers to the exercise of customer choice, and whether UK residents are ready to change their consumption habits to support or prefer consumption of electricity produced by offshore wind farms. This includes many practices such as: accepting a price increase, changing consumption patterns to better match supply, adopting demand management technologies, etc.
- C7-Finance (motivation): this refers to the willingness of finance suppliers to support offshore wind farm projects based on their perception of risk and of the future of the sector.
- C8-R&D motivation (motivation): this refers to the motivation of supply chain actors to invest in R&D projects.

Table 1 also displays 13 different directions of search:

- Low Levelised Cost of Electricity (LCoE): this refers to the long-standing search by the entire industry to lower the lifecycle costs of electricity produced by wind farms in order to make it competitive with traditional fossil fuel sources. This search can be broken down in many independent search categories. De-risking offshore wind farms searches currently focus on (S1) using project finance methodologies to contractually manage project risk (albeit at a high transaction cost) and (S2) on improving the reliability of cables (which are currently the weakest component). There are also many searches based on technology improvements such as (S3) increasing the scale of the turbines, (S4) technology innovations such as improving turbine designs and installation methods, and (S5) improvements to supply chain processes. There are also alternative technologies such as (S6) floating wind turbines. Operations and maintenance improvements are the last category of cost-reduction searches, with (S7) better design for maintenance vessels, (S8) the adoption of predictive maintenance technologies, and (S9) the improvement of load factors.
- Steady, level supply is another direction of search focusing on the intermittence problem. Not only wind farms have intermittent supply (when it is windy) but their output can be very volatile (i.e. subject to wind gusts). An important direction of search is (S10) the use of storage devices, either on a small timescale (for example grid storage for frequency regulation) or on a larger time scale (e.g. several days). Combining wind power with other sources of renewable energy (S11), ideally with a low correlation between the different energy sources, is another direction of search. Finally, the construction of deep offshore wind farms seeking stronger and steadier winds is the last direction of search (S12) in this category.
- Stand alone wind (S13): this refers to the search efforts associated with the target of generating 20% of UK electricity through wind farms. Instead of considering wind power as one fuel source in a diversified portfolio, this search is target-driven and technology-specific. It is espoused by pro-wind coalitions, whose members often view other renewable energy sources as competition threatening their income streams.

Table 2 shows the result of the q-analysis of the relationships between searches and constraints. Table 3 shows the measures of eccentricities for each search and for each constraint. The structure vector's norm for the searches is 4.47 and for the constraints 7.41. It indicates a rather complex set structure, and a dissymmetric one, as the structural complexity of the constraints space is 1.65 more complex that the view of the search space.

Table 2: Results of Q-analysis.

Direct Relationship	Indirect Relationship
q=5, Q_5=1, {S_9}	q=6, Q_6=1, {C_4}
q=4, Q_4=2, {S_9}{S_{13}}	q=5, Q_5=1, {C_4}
q=3, Q_3=1, {S_9,S_{13}}	q=4, Q_4=5, {C_2}{C_3}{C_4}{C_5}{C_8}
q=2, Q_2=3, {S_5,S_6,S_9,S_{13}}{S_1}{S_{10},S_{11}}	q=3, Q_3=5, {C_2,C_4}{C_3}{C_5}{C_7}{C_8}
q=1, Q_1=2, {S_1,S_3,S_6,S_9,S_{10},S_{11},S_{13}}{S_2}	q=2, Q_2=1, {C_2,C_3,C_4,C_5,C_7,C_8}
q=0, Q_0=1, {S_1,S_2,S_3,S_4,S_5,S_6,S_7,S_8,S_9,S_{10},S_{11},S_{12},S_{13}}	q=1, Q_1=1, {C_2,C_3,C_4,C_5,C_7,C_8}
	q=0, Q_0=1, {C_1,C_2,C_3,C_4,C_5,C_6,C_7,C_8}

Table 3: Eccentricities

Searches	Constraints
Ecc(S_1)=33%; Ecc(S_2)=50%	Ecc(C_1)=0%
Ecc(S_3)=0%; Ecc(S_4)=0%	Ecc(C_2)=20%
Ecc(S_5)=0%; Ecc(S_6)=0%	Ecc(C_3)=40%
Ecc(S_7)=0%; Ecc(S_8)=0%	Ecc(C_4)=42%
Ecc(S_9)=50%; Ecc(S_{10})=0%	Ecc(C_5)=40%
Ecc(S_{11})=0%; Ecc(S_{12})=0%	Ecc(C_6)=0%
Ecc(S_{13})=20%	Ecc(C_7)=25%
	Ecc(C_8)=40%

This analysis shows that the search for utilisation is the most complex as it faces many constraints, and it is one of the 2 most eccentric searches along with improving cable reliability. However, the cable reliability search is low in dimension, i.e. it is less constrained than the search for load factors. In terms of constraints intensity, the search for standalone wind is second.

The focus of this paper however is the analysis of the constraints space, and more specifically, as advocated by the theory of constraints, to identify the 'bottleneck'. Table 2 shows that the constraints space is much more complex than a standard linear assembly line. Constraints exist at different hierarchical levels of analysis. At the highest level of analysis, local acceptance (an opportunity factor) stands as the only constraint, and as a constraint to no less than 7 different search directions. The interpretation of this result is that the sustainable electricity sector of the future will bear little resemblance in terms of infrastructure and operations to the sector of today. Local resistance is a traditional resistance to change, a refusal to explore and research the 'non-familiar' (Pagell and Shevchenko, 2014), and as such it means that the design of an effective future system is impossible. It is interesting in this respect to compare the view of the UK which has increased the power of local residents and reinforced this constraint by opposition to many continental European countries where local residents cannot oppose a development but are only allowed to put conditions on it. Such a practice would result in eliminating many binding constraints (for example with S1, S6, S9, S10, and S11). However, in table 2, local acceptance is clearly the bottleneck to discovering the design principles of a sustainable sector.

At a lower level (q=4), 5 separate constraints appear as potential bottlenecks to the searches. In order to identify which one is the actual bottleneck, a q-analysis with weighted values (by opposition to binary values as in figure 1) would be required. Without performing this analysis in detail, one can set aside constraints C3 and C8 as being less important, revealing as potential bottleneck either opportunity or ability (grid, C2). This means that whereas q=6 represents the level of constraint of whole energy systems q=4 represents the current divide between the search for deep offshore or toward more integrated energy systems. It is only at the lower level of analysis (q=3) that these constraints together form a constraint (an OA interaction in the MOA terminology). This is the level akin to a dual critical path in project management. If local residents oppose wind farms, successful projects will be concentrated in remote, industrial areas. This results in more stress on the national grid as it may not be able to transport production (e.g. the existing transmission bottleneck between Scotland and England). This increases the need to site wind farms in other regions, which increases social resistance, etc.

CONCLUSION

An interpretive case study of the UK offshore wind sector concluded that the constraints of making the sector more sustainable was either the ability of the sector's CoP or exogenous factors to the sector. This paper introduced a q-analysis method of data analysis to resolve this indeterminacy. Thanks to q-analysis, the topological structure of the constraints to sustainability is revealed and shows not only a complex hierarchical pattern of linkages, or q-tunnels, between constraints but that opportunity constraints are indeed the most complex and highest-level constraints to address to help ongoing searches for sustainability to progress. This means that, at least in this case study, the constraints to sustainability are not within the supply chains but with its external stakeholders. It is a case where unsustainable consumption patterns expressed primarily through local residents opposition to infrastructure development results in the decreased sustainability of production. As the goal of this paper was to demonstrate the application of q-analysis for researching constraints to sustainability, it makes no claims about the prevalence of the conclusion, i.e. sustainable consumption as a constraint to sustainable production. Given the historical tendency of operations and technology management to rely on decoupling production from consumption matters, it is however relevant to call for more research investigating whether today's bottleneck to sustainability is more on the consumption side than on the production side.

APPENDIX

Appendix 1: Justification for Coding Ability Constraints

	Ability Constraints		
Search Direction	*Sites*	***Transmission***	***CoP Knowledge***
S2.Derisk–cable			*It is only through recent insurance claims that the industry has discovered that cables pose reliability issues. Solving this issue would reduce the transaction cost associated with projects, but this is an area where learning and research is ongoing.*
S3.Equipment Scale	*Larger turbines put additional demands on foundations and can limit the availability of suitable sites.*		
S5. Supply chain			*The UK has not supported the growth of an offshore supply chain in the last 30 years. Potential suppliers have limited knowledge of the industry and as a result are 'late movers' competing against well established clusters (Leseure et al., 2014)*
S6. Floating wind			*Floating wind offer an outstanding potential to site wind farms almost anywhere. Demonstration/test site exists but the technology is not commercially mature.*
S9. Utilisation		*The national grid is not designed to handle the output of wind farms. Some talk of an upcoming 'shock to the system'. This could led to curtailment which would result in lower load factors.*	*The industry functions through the balancing mechanism, i.e. a traditional chase demand approach to planning. Modern sales and operations planning are not explored and viewed with suspicion.*

	Ability Constraints		
Search Direction	***Sites***	***Transmission***	***CoP Knowledge***
S10. Wind with storage		*Matching intermittent supply sources with storage sites may not be possible with the existing grid.*	
S11. Mixed platforms		*Larger, mixed sites may be subject to the above transmission constraint depending on location.*	
S12. Deep offshore			
S13. Stand alone wind	*The best UK sites for wind power were identified by experts. As 50% were rejected, it is not clear that a sufficient number of sites with the requisite geographical diversity remain to reach the 20% target.*	*Experts are divided regarding the maximum share of offshore wind that can be handled by a national grid. Whether or not the target of 20% remains a debated question.*	*Wind farms are currently used as a priority alternative to fossils fuels. It is unclear what strategy will be used when these are decommissioned and when the margin of safety is reduced.*

Appendix2: Justification for Coding Opportunity Constraints

	Opportunity Constraints		
Search Direction	***Local Acceptance***	***Political (National) Acceptance***	***Consumer Behaviour***
S1.Derisk-Finance	*The frequency with which wind farm siting decisions are contested and the efforts deployed by opponents increase transaction costs and the perception of risk by financiers.*	*The UK is unique is terms of how much power is given to local residents. This is a much researched subject in the social science and authors describe the approach of the UK government as a 'unique way of doing things' (Toke, 2011).* *There has been intense political debate for and against wind power and the sector has regularly complained of inconsistent and volatile support. This increases perceived risks.*	
S3. Equipment Scale	*The trend toward larger turbine worsen the visual impact of wind farms and therefore the problem of local acceptance. This means that deep offshore sites, with their added costs, are becoming the only option.*		
S4. Technology innovation		*The Supply Chain Plan (DECC) is equivalent to a local content requirement and it may not have the expected benefits in terms of increasing competition and decreasing costs (Leseure et al., 2017).*	
S6. Floating wind	*The purpose of this technology is to remove the bed rock restriction of traditional monopile turbines. Wind farms could be installed anywhere, but are likely to meet further local opposition.*		

	Opportunity Constraints		
Search Direction	***Local Acceptance***	***Political (National) Acceptance***	***Consumer Behaviour***
S7. Vessels		*There are many ideas about improving the design of O&M vessels but it is estimated that these ideas will require at least 10 years to generate adequate return. Uncertainty about industry support during this timescale means that investments are often delayed (Crown Estate, 2012).*	
S9. Utilisation	*Utilisation issues created by the national grid can be addressed by updating the grid; but these projects are likely to meet their own local acceptance issues.*	*There has been much political turmoil around load factors and statistics were initially reluctantly made public. Low load factors require market subsidies and create a political dependency. Based on policy documents, it is difficult to assess whether or not this constraints is taken seriously or understood.*	*The current approach is to forecast demand through bids placed by electricity retailers, which prepare forecasts based on past demand and expected trend (e.g. weather). Utilisation, especially in the future, could be increased through demand management, but it is generally agreed that consumers will be unlikely to shift consumption patterns solely on the basis of electricity cleanliness.*
S10. Wind with storage	*Small and large storage sites are likely to face local opposition, either on land or offshore. Many promising storage technologies require large infrastructure.*		
S11. Mixed platforms	*This increases the size of the facilities and the constraints put on local sea users. Visual impact is increased.*		

	Opportunity Constraints		
Search Direction	***Local Acceptance***	***Political (National) Acceptance***	***Consumer Behaviour***
S13. Stand alone wind	*Whereas opinion polls report that 70%+ of the UK population is in favour of wind power, it is unclear why it faces such project rejection rates. This is called the 'social gap' (Bell et al., 2005).*	*The entire sector is heavily dependent on subsidies and change in regimes have important impact on the growth of the sector.*	

Appendix 3: Justification for Coding Motivation Constraints

	Motivation Constraints	
Search Direction	***Finance***	***R&D***
S1.Derisk-Finance	*Finance suppliers will continue to ask for risk premiums if they perceive wind farm projects to be risky.*	
S2.Derisk–cable	*The large cost of cable failure and the associated facility downtime mean that finance suppliers will continue to see the industry as above average risk.*	
S4. Technology innovation		*Technology innovation tends to be a commercially secretive area. The Crown Estate (2012) estimates that by collaborating on technology innovation at the front end of projects, CoP could reduce the LCoE by 5%.*
S5. Supply chain		*First movers in the offshore wind supply chain have benefitted from first mover advantages, and there is a reluctance from potential late followers to challenge them. The Crow Estate (2012) estimates that supply chain growth would reduce the LCoE by 4% and by a further 6% through competition effects.*

	Motivation Constraints	
Search Direction	***Finance***	***R&D***
S6. Floating wind		*There are intense disagreements in the industry regarding floating wind and opposing coalitions exist. This reduces the general motivation to invest in R&D.*
S8. Predictive Maintenance		*Although many countries (e.g. China) have installed state of the art predictive maintenance systems in their wind farms the UK is comparatively a late and reluctant adopter. The culture of cost minimisation means that there is little motivation for this search.*
S9. Utilisation		*The sector does not currently perceive utilisation to be a constraint. This is because it currently is not a material constraint, i.e. it is a future constraint once the weight of offshore wind in the energy portfolio increases.*
S10. Wind with storage	*The larger scale and commercially unproven technologies associated with these searches mean that they are 'ideas in principle' as the finance community is not showing any motivation to finance these projects yet.*	
S11. Mixed platforms		

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