

**Diagramming social practice theory:
An interdisciplinary experiment exploring practices as networks**

Sarah Higginson¹, Eoghan McKenna¹, Tom Hargreaves², Jason Chilvers² and Murray Thomson¹

¹Centre for Renewable Energy Systems Technology (CREST), School of Electronic, Electrical and Systems Engineering, Loughborough University, LE11 3TU, UK

²Science, Society and Sustainability (3S) Research Group, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK

July 2015

Abstract

Achieving a transition to a low-carbon energy system is now widely recognised as a key challenge facing humanity. To date, the vast majority of research addressing this challenge has been conducted within the disciplines of science, engineering and economics utilising quantitative and modelling techniques. However, there is growing awareness that meeting energy challenges requires fundamentally socio-technical solutions and that the social sciences have an important role to play.

This is an interdisciplinary challenge but, to date, there remain very few explorations of, or reflections on, interdisciplinary energy research in practice. This paper seeks to change that by reporting on an interdisciplinary experiment to build new models of energy demand on the basis of cutting-edge social science understandings. The process encouraged the social scientists to communicate their ideas more simply, whilst allowing engineers to think critically about the embedded assumptions in their models in relation to society and social change.

To do this, the paper uses a particular set of theoretical approaches to energy use behaviour known collectively as social practice theory (SPT) - and explores the potential of more quantitative forms of network analysis to provide a formal framework by means of which to diagram and visualize practices. The aim of this is to gain insight into the relationships between the elements of a practice, so increasing the ultimate understanding of how practices operate.

Graphs of practice networks are populated based on new empirical data drawn from a survey of different types (or variants) of laundry practice. The resulting practice networks are analysed to reveal characteristics of elements and variants of practice, such as which elements could be considered core to the practice, or how elements between variants overlap, or can be shared. This promises insights into energy intensity, flexibility and the rootedness of practices (i.e. how entrenched/ established they are) and so opens up new questions and possibilities for intervention.

The novelty of this approach is that it allows practice data to be represented graphically using a quantitative format without being overly reductive. Its usefulness is that it is readily applied to large datasets, provides the capacity to interpret social practices in new ways, and serves to open up potential links with energy modeling.

More broadly, a significant dimension of novelty has been the interdisciplinary approach, radically different to that normally seen in energy research. This paper is relevant to a broad audience of social scientists and engineers interested in integrating social practices with energy engineering.

Keywords: Social practice theory; network theory; geometry of practice; variant of practice; interdisciplinary; energy; demand management; flexible demand.

Introduction

Interdisciplinary research and the low-carbon energy challenge

Achieving a transition to a low-carbon energy system is now widely recognised as a key challenge facing humanity^{1, 2}. To date, the vast majority of research addressing this challenge has been conducted within the disciplines of science, engineering and economics utilising quantitative and modelling techniques³ (in this paper, a model is defined as a formalised representation of a natural system with its own internally consistent rules⁴). At the same time, there is growing awareness that meeting energy challenges requires fundamentally socio-technical solutions that seek to understand the co-evolutionary dynamics between technology and society⁵⁻⁷. Achieving this demands an interdisciplinary approach⁸⁻¹⁰. Whilst there is growing attention being paid to the challenges this poses to energy research¹¹, this has too often occurred as *ex post facto* reflection on attempted interdisciplinarity (or often multidisciplinarity – cf.¹²). There remain very few explorations of, or reflections on, interdisciplinary energy research in practice, that explicitly consider the multiple potential understandings, aims and approaches to interdisciplinarity and their productivities⁹.

The challenge of experimenting with and reflecting on interdisciplinary energy research in practice is a core objective of the Realising Transition Pathways research project, a collaboration involving social scientists, mechanical and electrical engineers, historians and economists, drawn from across nine UK universities. Reflection on interdisciplinarity undertaken during the first round of the project revealed that, despite great willingness, interdisciplinary approaches often ended or failed when collaborating around the engineering or economic models of the energy system used in the project^{13, 14}. Whilst the models were often open to receiving new input data from social science partners, this was seen as reflecting a ‘subordination-service’ mode of interdisciplinarity⁹ that positioned social scientists in the service of engineers. By contrast, social science partners in the consortium wished to open up debate around the underlying assumptions embedded within these models. Starting from this challenge, the second round of the project explicitly experiments¹ with different forms of collaboration between social scientists and engineers and examines the impacts this has on both the process and the outcomes of the research. This paper reports on one of the interdisciplinary experiments underway within the consortium that seeks to build new models of energy demand on the basis of cutting-edge social science understandings. It is worth noting that use of the term ‘experiment’ in this paper refers to a purposive intervention into ways of doing research that is explicitly reflective, rather than the narrower scientific use of the term, so that experimentation is considered a process of innovation, as reflected on by Bulkeley and Broto (2012).

Energy models, social practices and network theory

Quantitative models of energy demand occupy a central place in policy-decision making around energy futures. They currently inform assessments on a range of vital issues such as grid capacity¹⁵, demand management¹⁶ and the balancing of intermittent renewable generation^{17, 18}. Models are valuable precisely because they permit the spatial ‘scaling-up’ and temporal projection of insights about energy demand and so, although they cannot predict the future, they can be very useful aids for learning, thinking and decision-making. At the same time, many of the models that currently inform energy policy and assessments of UK energy futures are based on narrow and reductive assumptions about the nature and process of future energy transitions. For example, models often incorporate notions of rational choice or perfect foresight in decision-making¹⁹, include assumptions about smooth and optimal adoption of potentially disruptive technologies, and rely on uniform and homogeneous representations of often diverse and contested sociotechnical situations. Informing existing models with, and building new models that account for, recent developments in social science thus seems an obvious way to generate a more considered and critical process of dialogue and decision-making about the future evolution of energy demand.

This paper draws specifically on recent social science that focusses on applying the insights from Theories of Social Practice to energy demand. These Social Practice Theories (SPT) contend that energy demand is a by-product of practices such as cooking, showering, driving or laundry^{20, 21}. Understanding energy demand – whether today or in the future – therefore requires that attention be paid not to individual decision-making or processes of technology diffusion, but instead to practices and how they evolve and change over time. Practices themselves are understood to be heterogeneous configurations of a range of different elements including physical and mental skills and competencies; technologies and infrastructures; and images, ideas and meanings²²⁻²⁴. In this way, SPT embraces sociotechnical complexity and dynamism, recognising that the trajectory of different practices (and associated energy demand) is always shaped by a wide range of different and at times interacting influences²⁵.

In the UK at least, SPT is increasingly gaining traction in policy discussions about energy demand²⁶. At the same time, it remains some way from having the same kind of influence as theories such as ‘rational choice’ or ‘nudge’^{27, 28} at least in part because it resists simplistic forms of scaling-up across contexts. Indeed, for some²⁹, the irreducible complexity and dynamism of practices mean that they are not suitable for modelling or simulation as this risks oversimplifying complex social affairs. Although too rapid a rush to ‘model’ or ‘simulate’ practices risks misrepresenting their real and significant contribution to debates about energy demand, thinking critically about how one might model practices and experimenting with different approaches is in itself a valuable aim. In the context of interdisciplinary energy research, this paper will demonstrate that bringing SPT into close dialogue with different modelling approaches encourages social scientists to communicate their ideas more simply, whilst allowing engineers to think critically about the embedded assumptions in their models in relation to society and social change. This dialogue is an important step towards better interdisciplinary energy research.

The approach to achieving these ambitions starts small. Rather than starting by developing a new practice-based model as others have recently attempted ³⁰, the approach was instead to return to basic principles and think about new ways of diagramming and representing (but not yet modelling) practices, such as Bartiaux and Reátegui Salmón's ³¹ graphical representation of practices using multiple correspondence analysis, but here we draw instead on conventions and approaches developed in network theory. The network theory informing the approach taken in this paper has grown out of the natural and physical sciences, is quantitative in nature, and often focuses on networks of non-human entities ³². It has also been applied to the analysis of social networks of people ³³. Of course, there is a range of constructivist network approaches in the social sciences that are more qualitative in nature and account for heterogeneous arrangements of human and non-human actors, such as actor-network theory ³⁴ and assemblage theory ³⁵. Indeed, there are forms of arrangement theory that have quite strong commonalities with SPT itself ³⁶. Such constructivist approaches favour situated in-depth empirical studies of discrete actor-networks. The relationships and ontological differences between these different forms of network theory and their relations to practice theories demand further scrutiny in future work. The focus in this paper, however, is on exploring the potential of more quantitative forms of network analysis for diagramming, visualising and interpreting variants and relationships of practices. This makes it possible to draw on larger datasets, has the potential to interpret social practices in new ways, and also serves to open up potential links with energy modeling.

Within the broader goal of developing new forms of interdisciplinary collaboration, the core aim in this paper is thus to develop and experiment with a new method for diagramming social practices using network theory. This should help develop thinking about how the insights yielded by SPT might be included in future demand side energy models. Specifically, new empirical data drawn from a survey focussed on performances of laundry practices informs the diagrams. Laundry was selected in part because of the authors' own prior work ³⁷ but also because it has been a mainstay of much social practice-based research to date ³⁸⁻⁴⁰ and because it is often discussed as a temporally flexible load that could be targeted by demand side response initiatives ^{41, 42}.

The paper starts with an introduction to Theories of Social Practice (SPT), exploring some of its key concepts through diagrams and highlighting the network nature of practices. It then moves on to consider the application of network theory to SPT and why this is of consequence. In order to generate the empirical data upon which to base network graphs, a survey was conducted. This, and the method for generating the graphs, is described next. The following section reveals some of the possible network graphs resulting from this process and briefly discusses their relevance. Finally, the last section draws together some of the implications of the paper and identifies directions for future work. It also reflects on the process of conducting this interdisciplinary experiment.

Diagramming social practice theory (SPT) concepts

This section will review and critique a series of SPT concepts by diagramming them (a Glossary of the Terms covered in this section is also provided at the end of this paper). This has two advantages: diagrams are an already familiar means by which SPT is explained and it will make it possible to propose putting SPT concepts into a formal framework. Having derived a list of key concepts, the paper will consider whether network theory is well suited as an approach to extending the analysis of practices.

Practices, elements and connections

As outlined in the introduction SPT is an increasingly influential approach to understanding the underlying dynamics of energy use and posits that it is not appliances, houses or even people that use energy, but the performance of practices⁴³. The idea that practices are comprised of elements has been widely adopted. Different writers have highlighted different key elements in practices²³ but the most frequently cited is the Shove, Pantzar, Watson model, a “deliberately slim-line version of practice theory”²⁴, which has been adopted for three main reasons. First, this model actively incorporates material elements as part of the analysis which was important given this paper’s interest in energy. Schatzki, for example, does not include materials and non-human agents but sees them instead as arrangements amidst which practices unfold. Second, to facilitate the dialogue with an interdisciplinary audience, it was felt advisable to choose the simplest possible model with its more easily graspable language. Third, having only three elements simplified the diagramming of practices in this early experiment. By adopting this model, however, it has not been possible to distinguish between Schatzki’s ‘rules’ and ‘practical understandings’³⁶ or Gram-Hanssen’s ‘know how’ and ‘institutional knowledge’²³, both of which provide a good lever for those wanting to make policy recommendations and referring to this distinction could be a valuable for future work.

According to Shove et al., practices comprise material artefacts, conventions and competences (sometimes and henceforth in this paper called ‘stuff’, ‘image’ and ‘skill’)^{24, 44, 45}. Here ‘stuff’ includes “technologies, artefacts, spaces, bodies, structures, formats, compositions and ingredients. ‘Image’ represents the social and personal meaning attempted or achieved through practices, including emotion, aspiration, belief, identity and aesthetics. ‘Skill’ includes understanding, taste, competence, know-how or ‘procedures’ for accomplishment of a practice as learned socially and through performance”⁴⁶. Crucially, practice theorists note that practices are actualised, stabilised and changed through the active integration (or dis-integration) of these elements in particular performances of practices. Agency is not located in any one of these elements on its own but is distributed amongst all of them, and is indeed shared across practices, notwithstanding the increased appreciation of the agency of materiality (Hand et al. 2005).

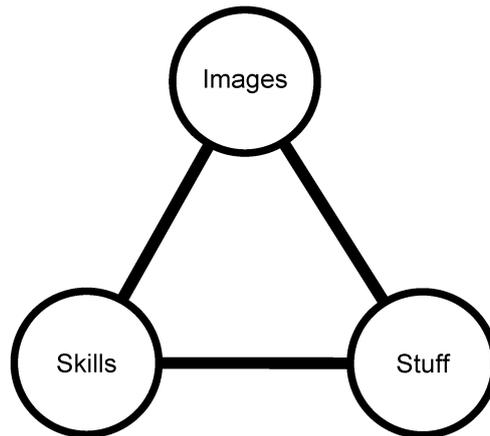


Figure 1 – Shove, Pantzar Watson model of practice.

Practices as performances and entities

Schatzki ⁴⁷ draws a crucial distinction between practices-as-entities and practices-as-performances. Where practice-as-entity refers to “a temporally unfolding and spatially dispersed nexus of doings and sayings” (Schatzki 1996, p.89) linked together through understandings, explicit rules and teleoaffective structures, by contrast, practice-as-performance refers to specific moments of integration between elements that occur when practices are enacted in particular local situations. In other words, practices-as-entities can be recognised to exist across time and space, even if they are not currently being enacted – the laundry being one such example as discussed in this paper. However, it is during situated and specific performances of laundry that the practice ‘lives’. A dialectical relationship exists between entities and performances because, whilst practices-as-entities may guide performances, it is through these performances that entities are (re)produced and either stabilised or changed (Warde, 2005). Further, and crucially, it is important to note that practices are never singular or fixed across time or space. Rather, and as Reckwitz notes, “a practice represents a pattern which can be filled out by a multitude of single and often unique actions reproducing the practice (a certain way of consuming goods can be filled out by plenty of actual acts of consumption)” (2002, p.250).

For some, the concept of practices-as-entities is seen as most important when seeking to intervene in practices because it helps to avoid the methodological individualism of more behaviourist approaches to social change ⁴⁸. However, for the purposes of this paper, the context-specificity, adaptability and variety of practices-as-performances are seen as likely to be significant in shaping future practice change. By observing and diagramming variety across multiple performances of ostensibly the same practice-as-entity, it may be possible to discern particular variants of the same practice as more or less dominant or important in particular times and places and, in so doing, to glean insights about the potential future trajectories of specific practices and how this has impacts across wider systems of practice. In other words, by looking at different performances of laundry and how these vary there is the potential to learn which variants of this entity use the most energy, have the greatest potential to be flexible or may become most dominant in the future.

Practices as networks

Kuijer (2014) suggests that the three elements categories (stuff, image and skill) are not single and homogenous but can be divided up. The 'stuff' of laundry is not merely the washing machine, for example, but also comprises the wash basket, clothes, detergent, water, electricity, the room in which the laundry takes place, etc., and so it is for each of the element categories. Each element category, in other words, is comprised of a "constellation of groupings of elements", as illustrated in Figure 2. The practice-as-performance is therefore conceived as a partial "manifestation" of the entity ⁴⁹. Different performances will use different combinations of interconnected elements and can therefore be conceptualised as having different geometries ⁵⁰. Over multiple performances, certain elements will acquire more weight (Kuijer describes them as being more or less 'essential' to the practice) because they appear more frequently.

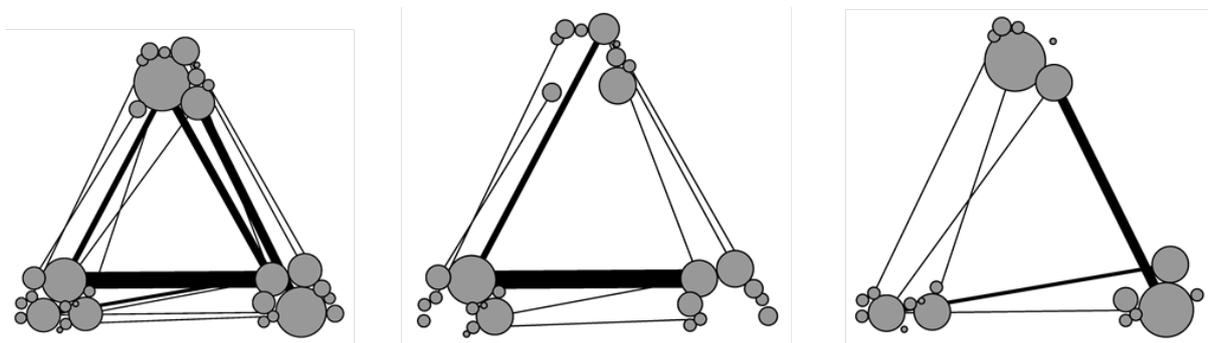


Figure 2 – Practice as an entity (left), and two individual performances (centre and right). Based on ⁴⁹.

It follows that different elements will be connected to each other in different ways. Except to stress their importance and that they are linked through performance, practice theorists have not had much to say about the connections between elements and so it is worth considering this in a little more detail. Starting with an individual performance of a practice, therefore, it is at least theoretically possible to observe and to note all the elements that appear. In an individual performance, every element and every connection can be conceived of as having equal weight simply because of its presence in the performance. Similarly, every element is equally connected with every other element in a single performance. However, over multiple performances, certain elements and the connections between them will be recognised as more frequent.

Taking a step back to look at the diagrams Kuijer produces to explain her model, the elements of a practice resemble a network in their relationship to each other. This network could be referred to as the 'internal structure' of the practice.

Networks between practices or variants of practices

Quite apart from the relationships within practices between elements, it is worth 'zooming out' (Nicolini 2012) to think about the relationships between whole practices. Everyday life is made up of multiple interlocking practices, both because they are co-located in time and space and because they share elements (Figure 3). Over repeated performances, practices can become linked through their elements. So, for example, a shared image of hygiene might link laundry and bathing, a shared skill such as self-care might link laundry with relaxation or shared stuff such as particular items of clothing might link laundry with work or school. This highlights two important concepts. The first is that the boundaries between practices are 'fuzzy'. At any particular time (in history or over a period such as a day) a variety of practices will be linked by shared elements in different combinations. This has been noted as a particular problem when trying to define, map or model practices⁴³. The second is that, because they are linked in this way, practices resemble networks both in terms of their internal structure (their elements are interconnected as above) and in relation to one another (their elements can be shared). Representing them using networks therefore seems appropriate, such as in Figure 3, where a network picture starts to emerge. Here colours are used to differentiate between elements of different types: white for Image, light grey for Skill, and dark grey for Stuff.

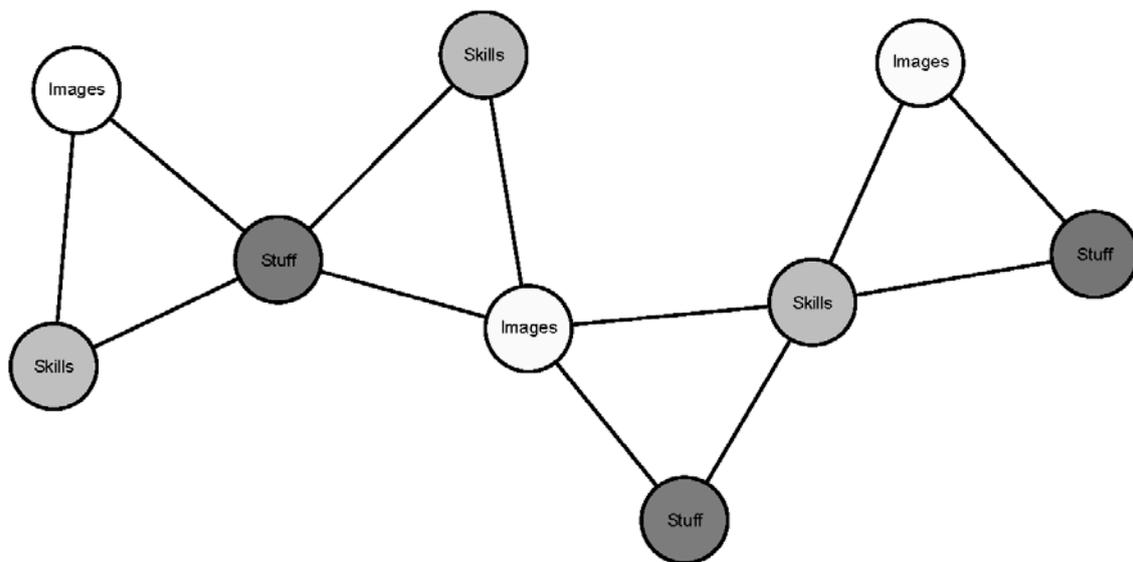


Figure 3 – Sharing of elements between practices. Four practice 'triangles' are represented here, each consisting of the three types of elements. Elements are distinguished by colour: white for Image, light grey for Skill, and dark grey for Stuff.

Kuijjer also suggests that performances are differentiated from one another and recognises that the way a practice is performed over time changes, which might be more or less resource intensive. One of the implications of these insights might be that performances with different geometries could be classifiable or recognisable as belonging to a particular type. In this paper, for example, different types of laundry practice are discussed, such as 'simple home laundry' and 'hand washing'. Pullinger et al.³⁸ suggest that different performances are configured in different (but identifiable and common) ways and that, through time and repetition, these can become recognised variants of a particular practice. Similarly to how practices share elements and are connected, variants (both within a single practice and between multiple practices) can be connected and could also therefore be represented as networks.

Suggesting some conventions

Having established the basic internal structure of practices and how they link with other practices and their variants, attention turns to how to represent these graphically. The next section will go on to consider the suitability of network theory for this task. Before that, however, some conventions are suggested for use in the rest of the paper, partly based on what has been seen so far.

As is suggested by Kuijjer's diagrams (Figure 2), it is a simple matter to represent the weight of an element using different sized 'bubbles'. It seems equally logical to represent links between elements through the thickness of the lines connecting them. At this stage, these links have not been given a direction but this may be an area of interest in future work. Kuijjer represents the category to which an element belongs – stuff, image and skill – by position (clustering them all together) but, while this is helpful in the simple representation of practices, it is of limited value for purposes of this paper as it implies a 'proximity' between elements of the same type, which does not necessarily exist; that is, between all the stuff, all the skills and all the images in a practice. During performances there may well be, for example, a stronger relationship between the 'image' of clean laundry as Fresh Smelling and White with the 'stuff' of Detergent and Washing Machine than there is between this 'image' of Clean and the now out-dated 'image' of clean laundry as Hygienic (and therefore boiled). In other words, the 'image' and 'stuff' in this example are probably more closely related than the 'image' is to the other 'image'.

Rather than using position, therefore, the element categories are represented by using colour, as outlined above. Instead, the position of the element 'bubbles' within each diagram will be used to represent importance and correlation (so strengthening the information provided by the size of the element bubbles and the number and thickness of the links between them).

Applying network theory to social practice theory

This section explores how network theory might be used to help diagram practices. To do that, it will provide a brief introduction to network theory and then use it to produce diagrams of practices using a hypothetical example.

Brief introduction to network theory

Network theory is concerned with the study of networks⁵¹. A network consists of a set of items called nodes, or vertices, and a set of connections between them, called edges. Examples of networks include the internet, predator-prey food webs, electricity distribution systems, and networks of acquaintances in social media. Network theory is based on the mathematics of graph theory, which gives a systematic procedure for keeping track of how items are related to each other to generate an entire system, as well as how each item contributes to the overall geometric representation of the system.

Examples of questions of interest to network theorists are:

- What are the characteristics of networks and do networks of different types share common features?
- How do networks form in the real world and how do they evolve?
- How resilient is a network to disturbance, such as the removal of a node?
- How do networks found in nature differ from those that are constructed from random processes?

Of particular interest for the purposes of this paper, network theory offers a scalable basis for visualising and analysing complex networks which can be used as a basis for dynamic modelling. It has been extensively applied to the study of social, biological, information and technical networks. Given this wide application of network theory, the proposal here is to explore its relevance to practices. As with SPT above, the aim is not to provide a comprehensive treatment of network theory concepts, but to illustrate its potential application to SPT. Readers interested in learning more about network theory are referred to the following reviews^{32, 51, 52}.

An illustrative laundry practice network

Just as the fundamental building blocks of practices are elements and the connections between them, the fundamental building blocks of a network are nodes and the connections between them, called edges. It is assumed, for the purposes of this paper, that there is a direct equivalence between nodes and elements, and between edges and connections. Going forward, these terms are used interchangeably.

For the purposes of the example, imagine that Table 1 contains a set of elements associated with laundry practice. These are the nodes of the illustrative laundry network.

Table 1 – Imaginary set of elements associated with laundry practice

Element	Type
Detergent	Stuff
Washing machine	Stuff

Sink	Stuff
Bucket	Stuff
Home-made detergent	Skill
Machine settings	Skill
Hand-washing	Skill
Cleanliness	Image
Environmental awareness	Image

Next, three individual performances of laundry are diagrammed. Each performance contributes a set of connections to the network, as shown in Figure 4. In this example, each performance involves four elements, and therefore six connections – elements that are not involved in the performance are not connected. As per this paper’s convention, the elements are coloured according to their type: white for image, light grey for skill, and dark grey for stuff. The position of the elements is arbitrary for the moment. Considering the three performances together, it is clear that some elements are shared. Detergent and Cleanliness are shared by performance 1 and 2, while Hand-Washing is shared by 2 and 3.

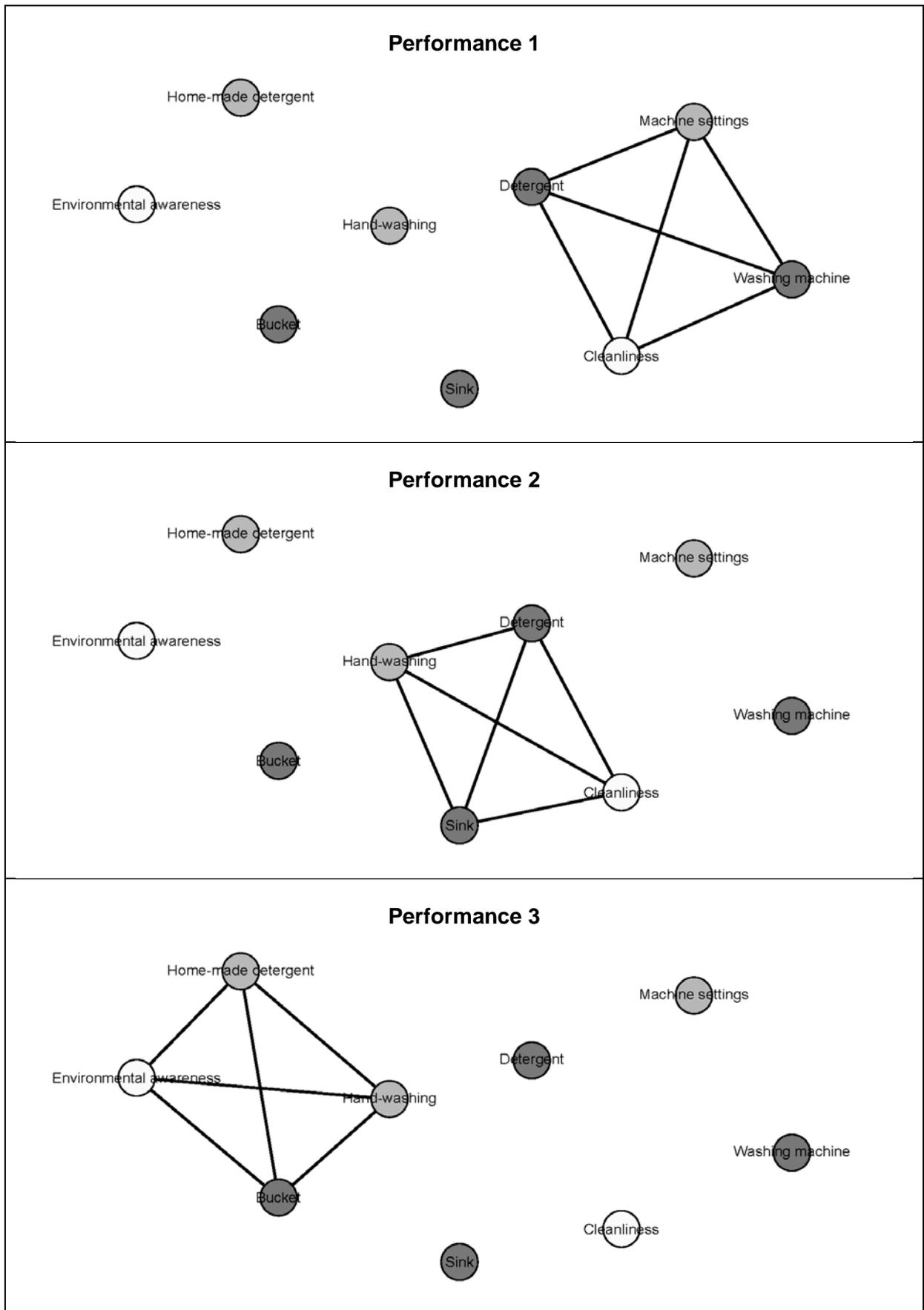


Figure 4 – Three graphs of individual performances of laundry

Figure 5 combines all three performances on a single network. All the connections from the three performances are visible but the sizes of elements and connections are not equal. The connection between Detergent and Cleanliness is twice the width (or weight) of the other connections because it appears in two performances, while the size of the elements is proportional to its degree, or the number of connections it has. Degree and weight are examples of local properties of the network, that is, properties of the nodes and edges, as opposed to the network as a whole. The important point here is that this visual technique of representing local properties is suited to representing both the probability of occurrence of a single element (by size of node), as well as combinations of elements (by the size of connections), both of which are important SPT concepts to be captured with this method.

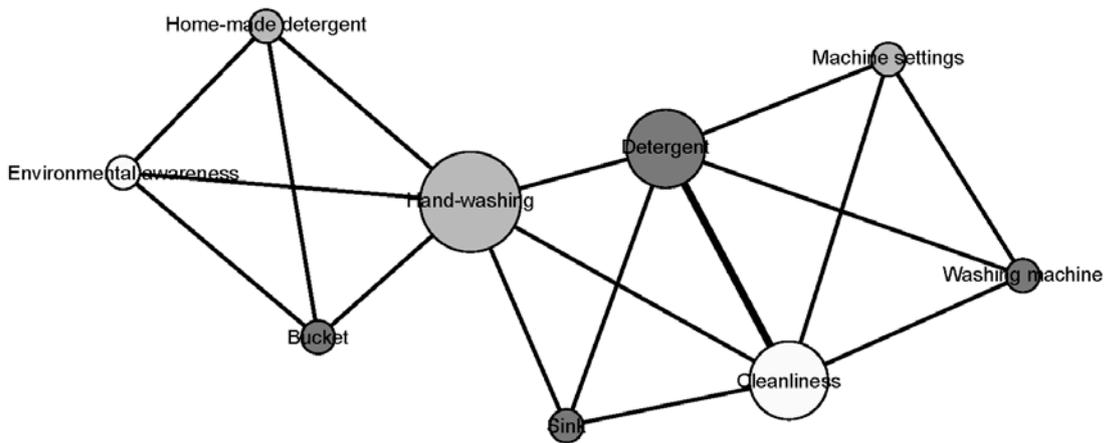


Figure 5 – Network of three laundry performances combined.

As the number of elements and connections increases, the arbitrary layout of elements can become increasingly ‘messy’ and inadequate. There are, as a result, different ways of distributing the elements in the graph in an intuitive, visually appealing way, such as, for example, trying to avoid crossed connections. Figure 6 shows the same network as before, but arranged using a ‘force atlas’ layout. This type of layout combines repulsive forces between all elements with attractive forces between connected elements. Elements with more connections between them are drawn together, while elements that have few connections are pushed to the edge. For example, the elements that were involved with performance 3 form a cluster that is relatively loosely bound to the ‘core’ elements, which in this case happen to be associated with performance 2 (highlighted in white). While this is a trivial example involving three performances, larger numbers of performances make the structure of the network increasingly visually apparent.

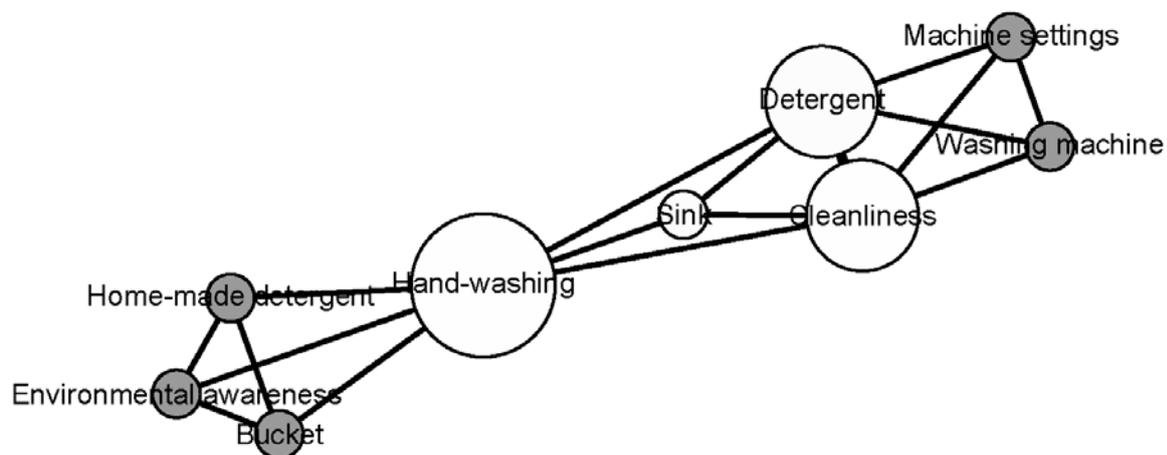


Figure 6 – A ‘force atlas’ layout of the example laundry network, with elements associated with performance 2 highlighted in white. All other elements are coloured in grey, regardless of their type.

Just as network theory provides methods for determining local properties, such as degree or weight, so it could provide methods for determining properties of clusters of elements, or of the network as a whole (its global properties). For example, eccentricity is a measure of how well integrated a cluster of elements is to the rest of the network. The mean shortest path between pairs of nodes gives an indication of how quickly information can travel across a network. Transitivity is a property that measures the likelihood that two nodes connected to a third node will also be connected together, for example, that “a friend of my friend is likely to be my friend”. Other properties include a measure of the complexity of the network, or connection homophily i.e. whether nodes of the same type are more likely to be connected together. These properties are often useful when dealing with or comparing large networks. Indeed, one of network theory’s strengths is that it is readily scaled up to analyse and visualise large complex networks consisting of many elements and connections.

Network theory is not only concerned with analysing the structure and properties of static snapshots of networks but is also interested in network dynamics. This can be broken down into two areas: network evolution⁵³ and processes taking place on networks⁵⁴. Network evolution is concerned with explaining how networks come to have specific properties according to different theories of how they grow i.e. through the addition of nodes and connections in some manner that is supposed to reflect how real networks behave. Processes by contrast deal with the flow of 'traffic' through a network, for example, the flow of information through the web, gossip through social networks or diseases through populations. From an SPT perspective, network evolution could be viewed as analogous to the study of how practices evolve over time, while processes could be viewed as comparable to performances percolating through a network of elements over time. Exploring the possibility and potential utility of developing dynamic models of practices will occupy further work.

These properties suggest a rich potential for linking network theory and SPT concepts. It would therefore appear to be qualified for the task of dealing with the whole range of practices-as-performances to practices-as-entities and, indeed, beyond, to multiple interconnecting practice-as-entities. In summary, network theory appears to be able to provide a framework for diagramming practice concepts and, furthermore, offers scope for future development. The next section will describe the data used to populate the network graphs and how it was collected.

Constructing a practice network from empirical data

Broadly the experiment described in this paper is concerned with constructing a network map of a practice and its variants. This paper limits its scope to mapping just one practice and does not attempt to trace its evolution over time or its connections to other practices. This section describes the collection of empirical practice data and how it was turned into information that could be graphically represented. The challenge was to determine what elements were present in the practice and how these were connected with each other. Graphically representing practices informed by empirical data represents a significant step forward.

Survey methods

Having decided how to graphically represent practices, it became necessary to collect data with which to 'populate' the element bubbles. In order to obtain this small scale empirical data a laundry survey of 27 students familiar with SPT was conducted. Basic demographic information (age, gender, nationality) was collected, as well as information about the timing and frequency of their laundry, whether it was triggered by anything in particular and whether other practices influenced why, how and how often they did their laundry. This reflects the researchers' overall interest in the timing of energy demand and assessing its possible flexibility.

The collection of data was inspired by The Patterns of Water report ³⁸, which is based on empirical data collected from a representative sample of 1,802 households in the South and South East of England between June and October 2011. They examined a number of water related practices, one of which was laundry, for which they identified six variants. Students were therefore asked to distinguish which of these six variants best described their normal laundry practice by responding to a statement and then listing all the elements present in their most recent performance of laundry. The elements were mapped against the performances in tabular form and then used to derive network graphs that enable the examination of the geometry of practices, as described below.

Results of the survey

The results of the survey of 27 students were encoded into an 'incident matrix' in excel, allowing a row for each student, each of which equates to a performance of laundry and organising the elements and other survey question responses in columns. The number of elements were rationalised to a limited degree by grouping similar answers together and incorrect responses were left out (for example, putting in numerous answers where only one was asked for).

As described previously, each element in the single performance reported by each student was considered to be of equal importance and equally connected to every other element in that performance. The elements listed as present in this performance were then considered, for the purposes of this experiment, to be part of the variant to which the students felt they conformed. This was based on the student's own identification with this variant, rather than through an analysis of the elements present in the performance.

The six variants of laundry are outlined in Table 2, which also provides the brief description to which the students were asked to respond when classifying the type of laundry they practiced and by means of which they were classified. The table also shows the breakdown of the percentages of participants in each study that belonged to each variant. A significant characteristic of this table is the fact that participants are listed by practice variant rather than according to their demographic profiles as this seemed an appropriate ‘first cut’ of the data when following an SPT approach.

Table 2 – Breakdown of % of participants according to variant of laundry practice ³⁸

Name of variant	Description of variant used in the survey	% sampled population in Patterns of Water Report’	% of participants in this paper’s Survey
Simple home laundry	“I wash all my clothes at home, in a full washing machine. I never change the settings on my washing machine.”	35%	44%
On-demand home laundry	“I mostly run the washing machine only when it is full, but sometimes I have to wash specific items of clothing ‘on demand’, so I run the machine part-full at these times.”	17%	7%
Simple outsourcing	“Most of the time I wash all my clothes at home in a full washing machine, but sometimes and for some items, I outsource my washing e.g. to a launderette, dry cleaners, nappy washing service etc.”	16%	4%
Attentive clean laundry	“I regularly change the settings on my washing machine to match the specific laundry items I’m washing.”	15%	22%
On-demand outsourcing	“Most of the time I outsource my laundry (e.g. at a launderette, dry cleaners, laundry services, ironing services etc) but occasionally I run the washing machine part-full for specific items.”	11%	7%
Hand Washing	“I wash all my clothes by hand”	6%	15%

It should be noted that the survey was small and not representative and so no relevance in the paper has been attached to the fact that the percentages differ from the Pullinger et al. report³⁸. That the participants were students might mean they would be less likely to use dry-cleaning services, whereas parents, had they been sampled, might have been more likely to use nappy services. The size of the sample means that this paper cannot contribute to an overall understanding of laundry practices per se, nor can it foster the understanding the careers of practices over time as practitioners age with practices or the ways in which age might have an impact on what variant of a practice is performed, but that is not its objective. Rather the attempt is to diagram these practices and so the data was collected to provide realistic enough information to populate those diagrams but no more significance than that should be attached to the actual content of the element bubbles or the particular shapes of the variants.

Questions relevant for assessing the flexibility of laundry practice were not analysed for this paper, as the focus here is on the methodology of constructing graphs and their possible utility, rather than on the meanings of those graphs. However, with a larger data set, the answers to the questions on frequency, rhythm and flexibility could feasibly be cross-referenced against the variants of laundry, so providing some insight into whether a particular variant was more or less entrenched, energy intensive or flexible. Similarly, it was noted but is not reported on how many elements were identified per performance as this too might suggest more or less complex practices and so could open up questions about how established particular practices are; an important consideration when trying to change them.

Constructing the network graph

To construct the network graph, a Matlab script was written to convert the survey incident matrix into two tables: a nodes table and a connections table.

The nodes table populates the network with a node for each element. This also included attributes for each element for example element-type (stuff, skill and image), the total number of times it was mentioned in the survey and number of mentions for each variant type. This is necessary in order to highlight in the graph which elements are associated with the variants.

The connections table consists of a row for each connection in the network. This identifies for each connection the source element, target element, type of connection (all are undirected) and weighting. The weighting of each connection was set to one. The total weighting of a connection in the final network is therefore the sum of the number of connections in the incident matrix. So if three performances involved both Washing Machine and Detergent, then the final weighting of the Washing Machine-Detergent connection would be three.

The tables were imported into Gephi – an open-source network visualisation and analysis tool – to produce the final network graphs. ‘Force atlas’ layouts were chosen to arrange elements and filters were used to highlight elements based on the node attributes specified in the nodes table, for example, to differentiate between element types or to highlight variants.

Having established that it is possible to graphically represent practices informed by empirical data, the paper will now move on to show what sort of network maps can be produced using this method.

Empirically-populated network graphs of laundry

This section describes a series of network maps of practices and their variants. Network maps of laundry, formally known as graphs, are presented based on the results of the survey described above. The distinguishing characteristics of the graphs are discussed with a focus on identifying degrees of overlap and difference between variants based on a formal definition of the sharing of elements. The idea is to show what is possible using this method, imagining that one had access to a large data set, rather than to provide insights into laundry or the geometries of its variants as such. The section ends by reflecting on the relevance and some of the implications of combining network theory and SPT.

Whole practice network graph

Figure 7 shows the overall picture of the data. It displays the network graph of elements based on the results of the survey of 27 individual laundry performances. Elements are coloured according to type, as before. All elements within a single performance are assigned equally weighted connections with each other. The weighting of the connections in the network indicates the relative frequency of pair-wise combinations of elements in the 27 performances. The size of the elements is proportional to their degree. A force-atlas layout is displayed.

The network in Figure 7 has distinguishing features. There is a cluster at its centre consisting of elements that were frequently cited together. These, perhaps are the homogenous 'essentials' of laundry. Stuff is the predominant type of element in this group. Surrounding this group are less frequently mentioned elements. These peripheral elements are connected to the centre group, but rarely connected to each other. As a result, the peripheral elements do not appear as clusters. An exception is the group of elements at the far right of the network (Favourite Items, Time, Special Occasions, and Noise). The concepts of central or peripheral elements will be returned to more formally further on in this section.

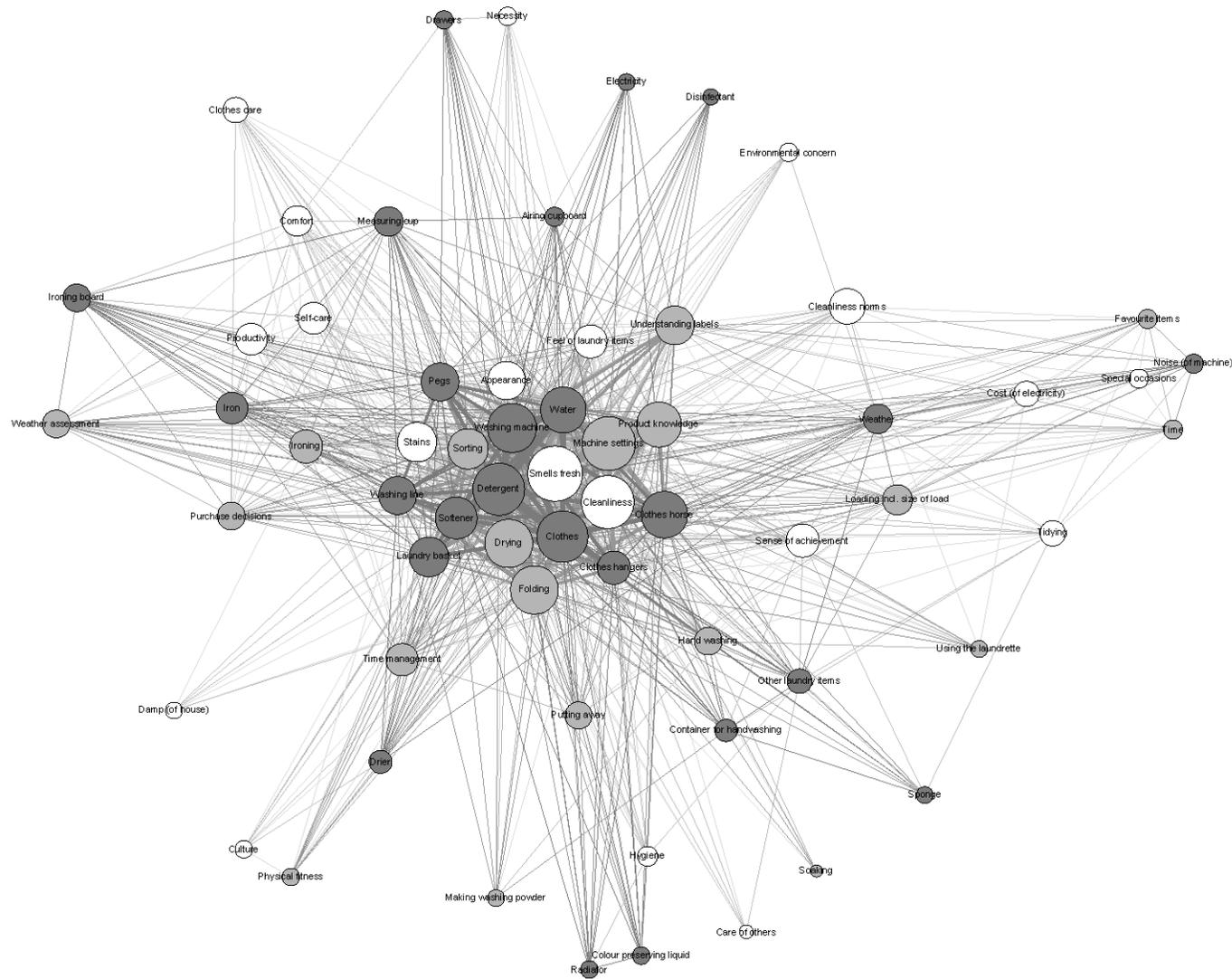


Figure 7 – Network of elements based on survey weightings. Image is coloured white, Skill is light grey, and Stuff is dark grey

Variant network graphs

The laundry variants are not obviously distinguishable in Figure 7. This corresponds with the finding from the Patterns of Water report ³⁸ which found that laundry is generally quite homogenous, with 95% of the population owning a washing machine which they use 2-3 times a week, mostly full and without changing the settings, and with hand washing and outsourcing (laundrettes, dry cleaning and nappy services) being rare.

Figure 8 therefore displays the different geometries of the six variants by highlighting in grey all the elements that were mentioned at least once within each variant. Connections are not shown, to make the diagrams clearer. Generally, variants with more performances have more elements associated with them. The variants all share some elements that appear in the centre of the network and are differentiated by elements at the periphery.

In Figure 8, Variants 1 (Simple home laundry) and 4 (Attentive clean laundry) have some similar characteristics. Both have a relatively large number of elements associated with them, including the majority of elements at the centre of the network. They both also have a relatively large number of peripheral elements which spread out from the centre in a multitude of directions. This indicates that within variants 1 and 4, performances are widely varied, at least in terms of the elements reported by the participants in this study. If the variant performances were more similar, then the variant geometries would be less spread out in all directions.

By contrast, the peripheral elements in both variants 5 (On-demand outsourcing) and 6 (Hand washing) spread from the centre in one, broadly similar, direction. While this is to be expected to certain extent due to the smaller numbers of performances, it would also be an indication of more similar performances within the variants – and, therefore, greater cohesiveness. The two variants also share elements, including some peripheral ones (Hand Washing, Sense of Achievement, and Other Laundry Items), indicating a certain similarity between them.

Variants 2 (On-demand home laundry) and 3 (Simple outsourcing) both have low numbers of performances. Partly for this reason, they both have a low number of associated elements and are not well-distinguished from other variants. For example, the elements associated with variant 3 are a sub-set of the elements associated with variants 1 or 4. Likewise, with the exception of one element, variant 2 is contained within the set of elements associated with variant 4. In other words, in this sample, only four variants of laundry are easily distinguishable. To be clear, however, no relevance should be attached to the fact that the percentages for the variants reported here differ from the Pullinger et al. report.

Although the geometries of each variant cannot be commented on due to the low numbers in the data set, these graphs suggest at least the possibility of diagramming practices in a useful way and identifying variant geometries and so go beyond the original hopes for this paper. These graphs, although not based on representative data, reveal characteristics like variability or cohesiveness of performances within variants, central and peripheral elements, and similarity and difference between variants. The fact is that it is possible to see a way of plotting a graph based on practice-based data, which is exactly what engineers hope to do. From a social sciences point of view this is also an exciting outcome as it provides a different view of practices (see also Bellotti and Mora (2014) who have also sought to represent practices graphically but with some important distinctions which are discussed in more detail below).

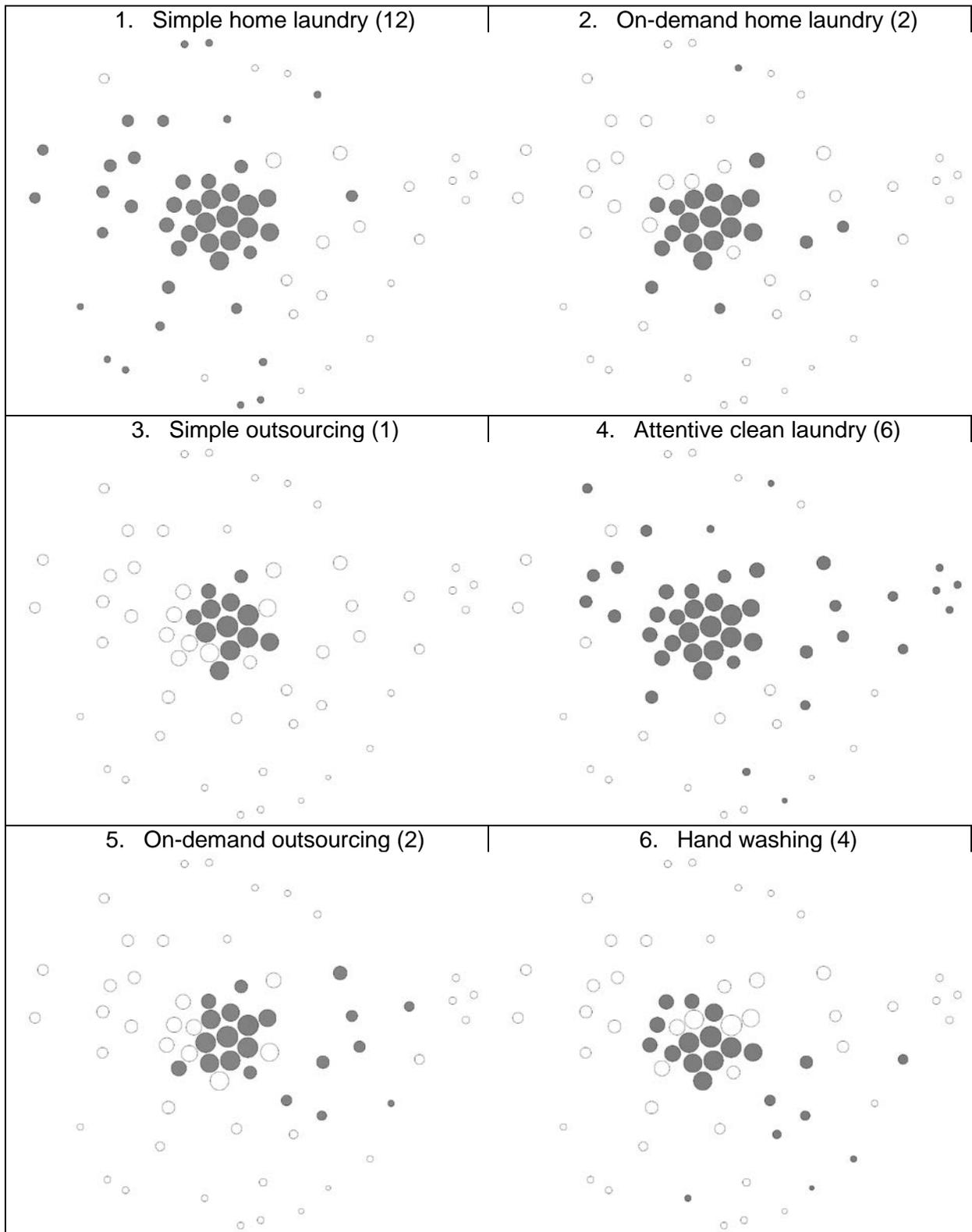


Figure 8 – Networks of laundry variants. The number of performances of each variant is indicated in brackets. The elements are highlighted in grey if they were mentioned at least once within each variant. All other elements are coloured white.

Core and peripheral elements

Before moving on to discuss the implications of this work more fully, it is necessary to first return more formally to the concept of central and marginal elements. Central elements are defined as 'core' to the practice; those which appear at least once in each variant and are shared by all variants. Marginal elements are 'peripheral'; defined here as those elements which are unique to a single variant. Elements that do not fall into either the 'core' or 'peripheral' groups logically form a third group, which is referred to as 'intermediary' – these elements are shared by some, but not all, variants.

Figure 9 illustrates this grouping of elements that are shared (or not) between variants. Core elements are highlighted in dark grey and are: 'stuff' in the form of Water, Clothes, Detergent, and 'image' in the form of Smells Fresh and Cleanliness. Light grey indicates the peripheral elements, which are greater in number than the core elements. The elements in white are the intermediary ones, shared by multiple variants, and are the most common.

This distinction between core and peripheral elements may prove useful when considering interventions in practices. Interventions focussed on the core elements, for example changing the meaning of Cleanliness or Smells Fresh, could be expected to have a consequence for the whole practice as, by definition, they are associated with every performance. By contrast, interventions focussed on peripheral elements (on one particular variant) might be effective agents for change within a variant or might offer an opportunity to streamline the practice.

Seeing the potential for geometries within variants is fascinating and suggests possibilities for development. In future it would be important to 'zoom out' ⁵⁵ and collect data on multiple practices so as to establish the connections between different variants of laundry and other practices as this is important for understanding flexible energy demand. The key question here would be: 'are different variants of laundry differently inter-connected with other practices?'. If so, this would demonstrate that different 'laundries' exist and this complexity and variety would need to be addressed in attempts to shift practices. Alternatively, it would potentially be possible to 'zoom in' further and map particular types of elements and the nature of the relationships between them. It might be useful to tackle meanings and norms, for example, as suggested by Pullinger et al. ³⁸ who found that cleanliness norms were cited as more important, and demonstrated much more diversity, than sociodemographic characteristics in deciding when to do the laundry.

From a practical perspective, it is worth noting the relatively large number of connections in the network shown above. This is the result of adopting a 'universal connection' convention – every element is equally connected to every other element within a performance. One consequence of this might be a reduced tendency of elements to cluster into groups. For example, Pegs, Washing Line, and Measuring Cup are all elements of Stuff that could reasonably appear in the same performance. The connection between Pegs and Measuring Cup, however, is perhaps less intuitive than it is for Pegs and Washing Line. Further investigation is recommended on the criteria for determining connections between elements and the characteristics of those connections (such as direction, strength, frequency) and the impact this could have on network graphs.

Finally, it is worth considering whether the proposed method (network theory) has proven to be a useful way to capture key SPT concepts in diagrams. The method seems to be capable of visually representing elements, performances, variants and entities. Connections between elements have been represented, as well as between variants of a single practice entity in the form of shared 'core' elements. Connections between different practice entities have not been represented, as the scope of the study was limited to a single practice, but it would seem feasible to be able to do this in future. Finally, the frequency of occurrence of elements and combinations of elements has been represented by the degree (of nodes) and weight (of connections) respectively. The ability to capture some of the key concepts in SPT within a formal framework would appear to make this a useful method to adopt in future practice-based work. The following section builds on this by synthesising the learning from the paper in order to discuss its broader relevance and implications.

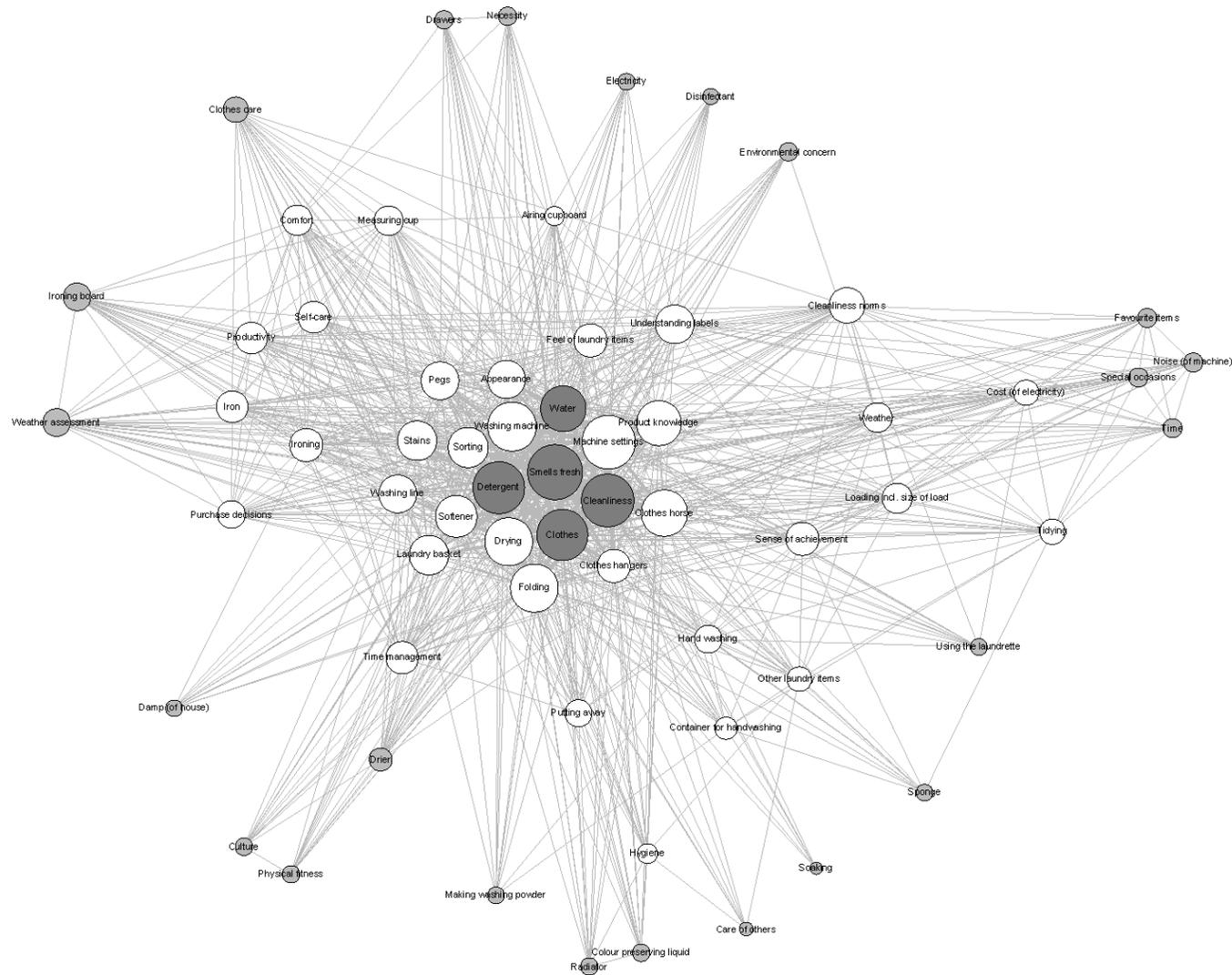


Figure 9 – Unifying elements (dark grey) are shared by all variants, while polarising elements (light grey) are found in only one variant. White elements are intermediary – shared by more than one variant, but not all

Reflections and conclusions

Diagramming practices

This paper originates out of an appreciation of the policy importance of energy demand models and the researchers' belief that the underlying dynamics of energy consumption are better represented by an SPT approach. In recognition of the need to create a new language so these two disparate disciplines can speak to each other, this paper had a simple, if ambitious, aim: to consider new ways of diagramming and representing practices drawing on conventions and approaches developed in network theory. It has been shown that practices can be conceived as networks, both in terms of their internal elements and their external connections to one another, and that it is therefore appropriate to use network theory to diagram them. In so doing, a framework for SPT that could provide a foundation for modelling practices in the future has been suggested and has also revealed new and interesting features of SPT.

The paper has some novel contributions. This is the one of the first times SPT and network theory have been linked. Bellotti and Mora ⁵⁶ have previously proposed the application of network theory to theories of practice, specifically to analyse data from a large survey of critical consumption behaviour in Italy. From a network perspective, a critical distinction between Bellotti and Mora's approach and the one presented here is that the nodes of the networks are different. The nodes in Bellotti and Mora's network are answers to survey questions which were not designed with practice theories in mind, while the work here more formally and explicitly defines the nodes as elements. The benefit of the explicit nodes-as-elements approach is that there is a clear and straight-forward link between the networks and the practice being represented.

More broadly, there is a subtle yet important conceptual difference between the two approaches. Bellotti and Mora use network theory to explore a sociological dataset and interpret the results from an SPT perspective – a social network analysis viewed through SPT. The approach in this paper differs by firmly adopting and questioning the critical viewpoint that 'practices are networks'; in this way more formally positioning this paper as part of a potentially new field of 'practice network analysis'.

This approach has demonstrated the possibility of graphically representing the geometry of variants of practice. Identifying core and peripheral elements within these geometries already opens up new questions about interventions as discussed above. Seeing practices represented like this reveals the degrees of overlap and amount of variation between practices. From a theoretical perspective, their sharing of many elements might trigger reflections such as how one practice is distinguished from another and might break down a priori assumptions about what constitutes different kinds of practices. It also inspires questions about cohesiveness and difference within variants, which may speak to the possibility of flexibility within practices. The diagrams also have a quality of immediacy which is able to reveal features such as the simplicity and complexity of different practices, prompting questions such as whether different variants of the same practice might be more or less energy intensive.

From a practical perspective, and perhaps this is ironic given the theoretical complexities just discussed, the method simultaneously makes it possible to deal with the fuzzy edges of practices and the context-specific and emergent nature of their performances because of its flexible network structure. It is not necessary to decide on whether an element belongs to one practice or another or even whether it is an image or a skill to be able to include it in the map.

This is where the next novel contribution comes into its own: producing diagrams of practices populated by empirical, practice-based data. The strength and novelty of this contribution is three-fold. First, it combines much of the information about the data and structure of the practice into one graph. This makes it more accessible but, hopefully, avoids the trap of reducing the insights of SPT so significantly as to undermine their contribution.

Second, the data drives the geometry of the practice. It is precisely the populating of the variant with data that reveals its geometry and, more generally, its geometry with respect to the geometries of all the other variants. Revealing the geometry of practices in this way allows them to be understood holistically but also promises interesting insights into the ecologies of practices and their interrelationships. Although these insights have been revealed by zooming into practices⁵⁵, it would also be possible to zoom out to gain an understanding of the links between practices to better assess their interconnectedness and possible flexibility.

Third, although the small data set here has constrained what could be said about laundry, the method suggests a way in which SPT can be 'scaled up'. This approach provides the tools to look at very large data sets and, in fact, more data would probably enhance the utility of the approach and the insights revealed. Ideas to explore this further are already being explored.

In terms of the possibilities of modelling practices, therefore, the paper has derived a scalable approach that can accommodate large data sets. Further work will be required to decide what data to collect and how to collect it. There will be a need to represent multiple practices and explore the connections between them. Indeed, there is important theoretical work to be done on the nature of the connections both between elements and practices, in terms of their strength, number, pattern and direction. Practically, this would enhance the ability of these graphs to reveal clusters. This implies the need to better understand the reasons for these connections, which highlights the need for continued interdisciplinary working.

In summary, network theory has proven to be sufficiently compatible with theories of practice such that the latter have not been overly compromised. It can serve as a useful vehicle for the formal representation of practices, both in terms of 'snapshots' of practices, as explored in this paper, but also in terms of their dynamics, which will be explored in future work.

Moving beyond network theory, the formal process of diagramming and representing practices presented here seems to be a constructive step towards understanding the relationship between SPT and quantitative models of energy demand. The experience has helped think through the data requirements for future attempts to further explore the geometries revealed in practice graphs. These promise insights into energy intensity, flexibility and the rootedness of practices (i.e. how entrenched/ established they are) and so opens up new questions and possibilities for intervention, as suggested above. Not only might practices be focused, changed or streamlined, as discussed earlier, but these changes might be able to be diagrammed so that the impact of interventions might be clearly demonstrable as differently structured network graphs.

At this stage it feels early to speculate too widely on the implications of this research. However, it does offer insights into the structure of practices; the fact that they are not irreducible to their elements as Reckwitz²² pointed out and that they are not separate, but connected. However, it may be that the important thing is to alter the geometry of the practice as a whole rather than focusing on individual elements and the core vs periphery elements might suggest sites of stability and variation within practices that help to do this: sources and origins of change as well as diversity. Looking at variants in this way shows diversity within practices which may suggest future trajectories. Tracking interventions might help both to map the altered structure of new variants, as well as revealing how they 'play' across the network as the geometry of individual practices and the ecologies of multiple practices are impacted over time. The policy relevance of this is that some variants will be less resource intensive or more flexible and can be promoted. However, more research is required to understand these questions fully.

Learning by doing: reflections on interdisciplinary energy research

It is clear that the attempt to combine SPT and network theory to produce diagrams of laundry practices has been both novel and productive with respect to thinking about practices and energy demand. At the same time, a second and arguably more significant dimension of novelty within this paper has been around experimenting with new forms of interdisciplinary energy research in practice. This concluding section reflects further on the nature and productivities of the interdisciplinary experiment attempted here, and raises some key implications for future interdisciplinary working.

This experiment sought to re-cast relations between social scientists and engineers and to explore new forms of relation in which social scientists lead the generation of new engineering models based on cutting-edge social theory. This represents a radically different starting point from most interdisciplinary energy research. In the terms of Barry et al's⁹ typology, this experiment thus represents a hybrid of an 'integrative-synthesis' mode of interdisciplinarity in which disciplines pragmatically work together to integrate findings and an 'agonistic-antagonistic' mode in which the tensions and incompatibilities between disciplines are actively drawn out as themselves generative of new possibilities.

As the preceding sections have shown, it is clear that approaching interdisciplinarity in this way has had a number of important productive effects and has made a considerable difference to both the kinds of discussions and approaches being engaged in, as well as to their outcomes. As such it is highly relevant to researchers required by their funding bodies to produce interdisciplinary outcomes. First, it is worth recognising the foundational importance of the six years of prior collaborative work between the Transition Pathways consortium partners and the explicit reflections on interdisciplinarity that this entailed^{13, 14}. Whilst this did not necessarily lead to the development of a 'common language' that is so often seen as essential to 'successful' interdisciplinarity⁵⁷, even more importantly, it developed the trusting relationships between partners necessary to air and respect differences and encourage the attempt to try radically new things. This is a significant achievement in its own right.

For the Engineers in the team, this entailed a completely new starting point to research in energy demand modelling. Rather than running new input data through incumbent models, this experiment has required that they start afresh and engage with new understandings of sociotechnical change, substantially different from those they were used to. By contrast, for the Social Scientists, the experiment demanded they go beyond the situated and in-depth case studies they are comfortable with, to engage instead in new ways of visualising and communicating ideas that, whilst certainly more reductive, are arguably more powerful than conventional prose accounts of practices. In so doing this has generated new ways in which SPT might think about 'scaling up' its application and engage with big data, which remains very far from the norm in this field. Whilst some who work with SPT might protest against this as a potentially reductive approach, the point being argued in this paper is that the conversation has, in itself, been productive. It has generated new kinds of discussions and insights about practices – relating to their variants, their relative complexity, and to core or peripheral elements across performances – that arguably would not have emerged through a more traditional, mono-disciplinary approach.

The process has been complicated, however, and there remain unresolved tensions that will continue to be productive in future work together. One such tension has been between the Social Scientists' desire for a kind of narrative approach that constantly reflects on and speaks back to the 'bigger picture' of debates about sociotechnical change and the Engineers' resolute attention to detail and desire for precise definitions of social science concepts. This has demanded diplomacy and compromise on both sides and, sometimes, setting aside particular points in order to allow the broader experiment to proceed. It is in part because of how these antagonisms were negotiated, that the more integrative aims of this paper have been achieved, generating a more symmetrical coming together of disciplines. The process is to be highly recommended, despite its difficulties, for it has been exciting, stimulating and, even, fun.

This paper has reported and reflected on just one of the experiments in interdisciplinarity being attempted within the Transition Pathways consortium and has shown that attempts to actually do and reflect on 'interdisciplinarity-in-practice' are productive in myriad ways. While the substantive focus has been on new ways of representing laundry-related practices, this paper also represents a rare attempt to demonstrate new forms of interdisciplinarity as themselves an emerging form of practice which should be encouraged in the energy research field and beyond. To be very clear, however, this is not a call for, or a claim of, a 'best practice' model of interdisciplinarity. In stark contrast, developing the practice of interdisciplinarity demands an avowedly experimental approach that actively pursues multiple modes or variants together and that explicitly reflects on the different yet interconnected productivities and effects that they each have. The hope is that this attempt will encourage other researchers from all disciplines to embark on similar journeys.

Glossary of Terms

Practice: There is a large body of literature on practices. For the purposes of this paper, they defined as heterogeneous configurations of a range of different, interacting elements including physical and mental skills and knowledge; technologies and infrastructures; and culture, ideas and meanings ²²⁻²⁴. Practices (and associated energy demand) are always shaped by a wide range of different and at times interacting influences ²⁵ making them a far broader concept than behaviour.

Element: The idea that practices are comprised of elements has been widely adopted. Different writers have highlighted different key elements in practices ²³ but the most frequently cited is the Shove, Pantzar, Watson model used here which attributes practices with three elements; stuff, image and skill. Kuijer ⁴⁹ suggests that the three elements categories (stuff, image and skill) are not single and homogenous but can be divided up and this concept is drawn on extensively in this paper.

Connection: It could be said that the fundamental building blocks of practices are elements and the connections between them. When practices are enacted, their elements combine in different ways and so can be said to be connected. Thus far, SPT has not had much to say about the connections between elements, something this paper starts to address.

Practice as entity or performance: Schatzki ⁴⁷ draws a crucial distinction between practices-as-entities and practices-as-performances. Practices-as-entities exist even if they are not currently being enacted – the laundry being one such example as discussed in this paper. However, it is during situated and specific performances (or enactments) of *doing* laundry that the elements interact and the practice comes to life (and uses energy).

Variant: Pullinger et al. ³⁸ suggest that different performances of a practice are configured in different (but identifiable and common) ways and that, through time and repetition, these can become recognised variants of a particular practice. Similarly to how practices share elements and are connected, variants (both within a single practice and between multiple practices) can be connected and could also therefore be represented as networks.

Acknowledgements

The authors gratefully acknowledge an early reading suggestion by Dr David Shipworth which planted the seed of inspiration from which this work grew.

All authors contributed equally in the preparation of this manuscript and are grateful for the valuable comments from the reviewers and editors which have contributed to the improvement of their contribution.

This work was supported by the Engineering and Physical Sciences Research Council, UK, within the Realising Transition Pathways project (EP/K005316/1). Research data for this paper is available on request from the corresponding author.

Conflict of interest: None.

References

1. Sautter JA, Landis J and Dworkin MH. Energy Trilemma in the Green Mountain State: An Analysis of Vermont's Energy Challenges and Policy Options, *The. Vt.J.Envnt.L.* 2008; 10: 477.
2. Hammond GP and Pearson PJG. Challenges of the transition to a low carbon, more electric future: From here to 2050. *Energy Policy* 2013; 52: 1-9.
3. Sovacool B. Energy studies need social science. *Nature* 2014; 511: 529-530.
4. Keirstead J, Jennings M and Sivakumar A. A review of urban energy system models: Approaches, challenges and opportunities. *Renewable and Sustainable Energy Reviews* 2012; 16: 3847-3866.
5. Verbong G and Loorbach D. *Governing the energy transition: reality, illusion or necessity?*. 1st ed. Abingdon, UK: Routledge, 2012.
6. Shove E, Lutzenhiser L, Guy S, et al. Energy and social systems. *Human choice and climate change* 1998; 2: 291-325.
7. Shove E. Gaps, barriers and conceptual chasms: theories of technology transfer and energy in buildings. *Energy Policy* 1998; 26: 1105-1112.
8. Nowotny H, Scott P and Gibbons MT. *Re-thinking science: knowledge and the public in an age of uncertainty*. 1st ed. Cambridge: John Wiley & Sons, 2001.
9. Barry A, Born G and Weszkalnys G. Logics of interdisciplinarity. *Economy and Society* 2008; 37: 20-49.
10. Lyall C, Bruce A, Tait J, et al. *Interdisciplinary Research Journeys: Practical Strategies for Capturing Creativity*. 1st ed. London, UK: Bloomsbury Publishing, 2011.
11. Winskel M. Embedding Social Sciences in Interdisciplinary Research: Recent Experiences from Interdisciplinary Energy Research. *Science as Culture* 2014; 23: 413-418.
12. Petts J, Owens S and Bulkeley H. Crossing boundaries: interdisciplinarity in the context of urban environments. *Geoforum* 2008; 39: 593-601.
13. Hargreaves T and Burgess J. Pathways to Interdisciplinarity: A technical report exploring collaborative interdisciplinary working in the Transition Pathways consortium. Centre for Social and Economic Research on the Global Environment Working Paper EDM 10-12. Norwich: University of East Anglia, 2010. Available online: http://www.cserge.ac.uk/sites/default/files/edm_2010_12.pdf [last accessed 16.07.15].
14. Longhurst N and Chilvers J. INTERDISCIPLINARITY IN TRANSITION? A Technical Report on the interdisciplinarity of the Transition Pathways to a Low Carbon Economy consortium. Norwich: University of East Anglia, 2012. Available online: http://www.bath.ac.uk/lowcarbon/news/Interdisciplinarity_in_Transition_FINAL_REPORT_De_c_2012.pdf [last accessed 28.07.15].

15. Pudjianto D, Castro M, Strbac G, et al. Transmission infrastructure investment requirements in the future European low-carbon electricity system. In: *10th International Conference on the European Energy Market (EEM)*, Stockholm, Sweden, May 27-31 2013. IEEE.
16. Barton J, Huang S, Infield D, et al. The evolution of electricity demand and the role for demand side participation, in buildings and transport. *Energy Policy* 2013; 52: 85-102.
17. Grünewald P, McKenna E and Thomson M. Keep it simple: time-of-use tariffs in high-wind scenarios. *Renewable Power Generation, IET* 2014; 9: 176-183.
18. McKenna E, Grünewald P and Thomson M. Going with the wind: temporal characteristics of potential wind curtailment in Ireland in 2020 and opportunities for demand response. *Renewable Power Generation, IET* 2015; 9: 66-77.
19. Kannan R and Strachan N. Modelling the UK residential energy sector under long-term decarbonisation scenarios: Comparison between energy systems and sectoral modelling approaches. *Appl Energy* 2009; 86: 416-428.
20. Shove E and Walker G. What is energy for? Social practice and energy demand. *Theory, Culture & Society* 2014; 31: 41-58.
21. Warde A. Consumption and theories of practice. *Journal of consumer culture* 2005; 5: 131-153.
22. Reckwitz A. Toward a Theory of Social Practices A development in culturalist theorizing. *European journal of social theory* 2002; 5: 243-263.
23. Gram-Hanssen K. Understanding change and continuity in residential energy consumption. *Journal of Consumer Culture* 2011; 11: 61-78.
24. Shove E, Pantzar M and Watson M. *The dynamics of social practice: everyday life and how it changes*. 1st ed. Thousand Oaks, CA: Sage, 2012.
25. Røpke I. Theories of practice—New inspiration for ecological economic studies on consumption. *Ecol Econ* 2009; 68: 2490-2497.
26. Chatterton T and Anderson O. An Introduction to Thinking About 'Energy Behaviour': a multi-model approach. London, UK: DECC, 2011. Available online: <http://eprints.uwe.ac.uk/17873/> [last accessed 10.12.12].
27. Thaler RH and Sunstein CR. *Nudge: Improving decisions about health, wealth, and happiness*. 1st ed. New Haven: Yale University Press, 2008.
28. Dolan P, Hallsworth M, Halpern D, et al. MINDSPACE: Influencing behaviour through public policy. London, UK: Cabinet Office, 2010. Available online: <http://www.instituteforgovernment.org.uk/sites/default/files/publications/MINDSPACE.pdf> [last accessed 28.07.15].
29. Schatzki TR. A primer on practices. In: Higgs J, Barnett R, Billett S, et al (eds) *Practice-Based Education: Perspective and Strategies*. Rotterdam: Sense Publishers, 2012, p.13.

30. Balke T, Roberts T, Xenitidou M, et al. Modelling Energy-Consuming Social Practices as Agents. In: Miguel, Amblard, Barceló, et al (eds) *Advances in Computational Social Science and Social Simulation*. Barcelona: University of Barcelona, 2014, p.1.
31. Bartiaux F and Salmón LR. Are there domino effects between consumers' ordinary and 'green' practices? An analysis of quantitative data from a sensitisation campaign on personal carbon footprint. *International Review of Sociology* 2012; 22: 471-491.
32. Dorogovtsev SN and Mendes JF. Evolution of networks. *Adv Phys* 2002; 51: 1079-1187.
33. Scott J and Carrington PJ. *The SAGE handbook of social network analysis*. 1st ed. London: SAGE, 2011.
34. Latour B. *Science in action: How to follow scientists and engineers through society*. 1st ed. Harvard: Harvard University Press, 1987.
35. Irwin A and Michael M. *Science, Social Theory & Public Knowledge*. 1st ed. Maidenhead: Open University Press, 2003.
36. Schatzki TR. *Site of the Social: A Philosophical Account of the Constitution of Social Life and Change*. 1st ed. Pennsylvania: Penn State University Press, 2002.
37. Higginson S, Thomson M and Bhamra T. "For the times they are a-changin'": the impact of shifting energy-use practices in time and space. *Local Environ* 2013: 1-19.
38. Pullinger M, Browne A, Anderson B, et al. Patterns of water: The water related practices of households in southern England, and their influence on water consumption and demand management. Lancaster, UK: Lancaster University, 2013. Available online: <http://www.sprg.ac.uk/projects-fellowships/patterns-of-water/patterns-of-water-final-report> [last accessed 07.05.15].
39. Shove E. *Comfort, cleanliness and convenience: The social organization of normality*. 1st ed. Oxford: Berg, 2003.
40. Jack T. Nobody was dirty: Intervening in inconspicuous consumption of laundry routines. *Journal of Consumer Culture* 2013; 13: 406-421.
41. Roscoe AJ and Ault G. Supporting high penetrations of renewable generation via implementation of real-time electricity pricing and demand response. *Renewable Power Generation, IET* 2010; 4: 369-382.
42. Timpe C. Smart Domestic Appliances Supporting the System Integration of Renewable Energy. Brussels: European Commission, 2009. Available online: http://www.smart-a.org/SmartA_Project_Final_Brochure_2009.pdf [last accessed 10.12.12].
43. Higginson SL, McKenna E and Thomson M. Can practice make perfect (models)? Incorporating social practice theory into quantitative energy demand models. In: *Proceedings of the 3rd Behave Energy Conference*, Oxford, UK, 3-4 September 2014. EST-UKERC.
44. Shove E and Pantzar M. Consumers, Producers and Practices Understanding the invention and reinvention of Nordic walking. *Journal of consumer culture* 2005; 5: 43-64.

45. Pantzar M and Shove E. Understanding innovation in practice: a discussion of the production and re-production of Nordic Walking. *Technology Analysis & Strategic Management* 2010; 22: 447-461.
46. Scott K, Bakker C and Quist J. Designing change by living change. *Des Stud* 2012; 33: 279-297.
47. Schatzki TR. *Social practices: A Wittgensteinian approach to human activity and the social*. 1st ed. Cambridge: Cambridge University Press, 1996.
48. Spurling N, McMeekin A, Shove E, et al. Interventions in practice: re-framing policy approaches to consumer behaviour (Sustainable Practices Research Group Report), 2013. Available online: <http://www.sprg.ac.uk/uploads/sprg-report-sept-2013.pdf> [last accessed 28.07.15].
49. Kuijer L. Implications of Social Practice Theory for Sustainable Design (PhD Thesis). Delft: Delft University of Technology, 2014. Available online: <http://studiolab.ide.tudelft.nl/studiolab/kuijer/thesis/> [last accessed 28.07.15].
50. Shove E. Energy transitions in practice: the case of global indoor climate change. In: Verbong G and Loorbach D (eds) *Governing the Energy Transition: Reality, Illusion or Necessity?*. Abingdon, UK: Routledge, 2012, p.51.
51. Newman ME. The structure and function of complex networks. *SIAM Rev* 2003; 45: 167-256.
52. Strogatz SH. Exploring complex networks. *Nature* 2001; 410: 268-276.
53. Hellmann T and Staudigl M. Evolution of social networks. *Eur J Oper Res* 2014; 234: 583-596.
54. Boccaletti S, Bianconi G, Criado R, et al. The structure and dynamics of multilayer networks. *Physics Reports* 2014; 544: 1-122.
55. Nicolini D. *Practice theory, work, and organization: An introduction*. 1st ed. Oxford: Oxford University Press, 2012.
56. Bellotti E and Mora E. Networks of practices in critical consumption (in press). *Journal of Consumer Culture* 2014.
57. Bracken LJ and Oughton EA. 'What do you mean?' The importance of language in developing interdisciplinary research. *Transactions of the Institute of British Geographers* 2006; 31: 371-382.