# Using Natural Language Processing (NLP) to assess changes in transdisciplinary understandings across a large research consortium

**Daniel Black[1,2], James Gopsill[3], Ges Rosenberg[3], Taru Silvonen[3], Aman Kukreja[3], Ben Hicks[3]**

[1] Population Health Sciences, University of Bristol, Bristol, UK

[2] Daniel Black + Associates | db+a, Bristol, UK

[3] School of Electrical, Electronic and Mechanical Engineering, University of Bristol, Bristol, UK

*** Correspondence:**

Corresponding Author

Daniel.Black@bristol.ac.uk

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# 1 Abstract

Researching how to create just and sustainable futures for all requires innovative and mission-oriented transdisciplinary approaches. This article sets out our approach and findings following the assessment, using Natural Language Processing (NLP), of the development in transdisciplinary understandings across a large and newly-forming research consortium as it changed over the six-year period of delivery (2019-2025). Two outcomes were sought from this assessment: i) learning to improve the transdisciplinary working in new, large research teams aiming to solve complex global challenges; and ii) improvement of use of NLP for this kind of exercise.

A research-on-research workstream provided qualitative data from 63 semi-structured interviews carried out with 39 consortium members, with three rounds of interview being conducted in Years 2, 3 and 5 of the programme. Drawing on this data, a 'dual approach' to NLP was used to assess changes over time and by discipline: i) co-word clustering of full transcripts; and ii) analysis of vocabulary identified as transdisciplinary.

The co-word clustering identified nine themes: new approaches (to operationalisation), case studies, the urban development context, mission-orientation, shared understandings, plural understandings, project structure and phasing, and collaboration. The analysis of transdisciplinary vocabulary indicated a clear convergence across disciplinary areas over six years and a small set of useful, jargon-free words (15 - 25% of 242 identified words were used across the four disciplinary areas). The results and analysis point to some useful findings and potential for improvement, but significant limitations were identified that would need addressing including: interpretation, thematic coherence, data quantum, inclusion of interviewer vocabulary, changes in programme development, normalisation and threshold determination. The approach was labour intensive, though future iterations should be much less so if the limitations can be addressed.

# 2 Introduction

## 2.1 The challenge of evaluating research operationalisation in real time

Creating just and sustainable futures for all requires large inter- and transdisciplinary research (IDR/TDR) consortia that bring together a wide range of experts from within and outside academia. While these types of collaborative approaches can stimulate innovation and offer the potential for comprehensive problem-solving, they also present significant management and communication challenges, especially in newly-forming, large or geographically and linguistically dispersed consortia [1]. Differing disciplinary languages, conceptual frameworks, and epistemological assumptions can hinder the development of shared understanding - an essential foundation for effective collaboration, integration of knowledge, and project success [2].

As a minimum, IDR is generally accepted to involve the collaboration of scientists from at least two disciplines who cooperate to achieve shared results, integrating concepts, methods and principles in the process [3]. The exact definition of TDR remains contested, though it has been broadly described as not only the integration of knowledge from different science disciplines, but also of "*(non-academic) stakeholder communities*", and as such is seen as essential in addressing real world problems [4, p.4]. In both cases, the interaction should result in innovation beyond what is usually possible within disciplinary siloes or without non-academic involvement respectively.

Evaluating the extent to which a transdisciplinary team has achieved shared understanding is a nontrivial task, especially in large-scale projects aimed at solving complex global challenges, where effective stakeholder representation and involvement is inherently challenging, and where interactions are distributed across time, institutions, and communication formats [5]. Traditional research methods present their own challenges. Qualitative analysis in research requires specialist insight and expertise and is often time-consuming [6]. To take a more specific example, static measurement tools, such as surveys, are limited in their ability to capture the dynamic, evolving, and context-rich nature of interdisciplinary dialogue [7, 8]. While analysis of core project data – e.g. meeting transcripts, reports, collaborative documents, and digital communications – can capture much of the dynamics and content, it is not necessarily representative of the whole project team, nor does it embody the 'behind-the-scenes' view [9, 10].

An approach that may have the potential to address some of these limitations is Natural Language Processing (NLP). Common applications of NLP so far include: automated theme modelling and clustering to reveal thematic drift across time; semantic-similarity and embedding methods to quantify conceptual overlap between disciplines; named-entity recognition and knowledge-graph construction to surface stakeholder networks and modelled concepts; and sentiment or discourse analysis to track shifts in framing and reflexive language in reports and communications [11, 12]. These approaches have been shown to augment qualitative coding and make longitudinal comparisons feasible across very large corpora generated by multi-year consortia [13, 14]. NLP has also proved useful in programme evaluation within education (e.g. characterising outputs, detecting emergent themes, and automating parts of synthesis), though caution is needed given that algorithmic outputs require careful validation against domain expertise to avoid over-interpretation: results suggest, for example, that NLP did not provide the granular detail that a traditional qualitative analysis would elicit, but it did provide a series of themes that could serve as a starting point for more nuanced analysis [6].

In addition to learning how to improve research operationalisation in these emergent contexts, we wanted to understand whether NLP might offer a scalable, reproducible alternative to research programme evaluation. More specifically, we wanted to assess its ability to allow for real time 'course corrections', the potential for a more rapid response, and for closing the loop on language and activities/leadership actions. To that end, we have developed and evaluated an approach that uses

NLP to analyse interview data gathered at the start, middle and end of a major six-year research programme.

Two separate outcomes were sought from this exercise: i) learning to improve the transdisciplinary working in new, large research teams aiming to solve complex global challenges; and ii) improvement of use of NLP for this kind of exercise. Under these two outcomes, we set out three objectives: i) to understand how language across the team changed using dictionary and theme analysis; ii) to explain the dynamics of language (e.g. commonality and variance across disciplines, mapping to events); and iii) to conclude with what we can learn from this in terms of the two aforementioned outcomes sought. Simply put, the overarching research question is: what can we learn from analysing these interviews using language analysis?

In this paper, we present our methodological framework, describe the NLP techniques employed, and discuss findings that might explain the dynamics of shared understanding within the project team. Our work contributes to both the theory and practice of transdisciplinary collaboration, offering insights into how far language-based metrics might serve as proxies in supporting conceptual alignment and team cohesion.

### 2.2 Background and timeline of case study programme activities

The UK-based consortium involved 57 academic staff in total (40 at any one time) supported by two to three dedicated 'professional services' staff in project management, administration and communications. The researchers were from a wide range of academic disciplines based across six Universities. The mission of the group was to investigate and address the upstream determinants of non-communicable disease in urban settings using a stakeholder-informed systems approach. Initial partnership arrangements were with two local government authorities resourced by a full-time researcher-in-residence in each location. The consortium engaged and involved hundreds of public, private and third sector stakeholders throughout the programme, developing partnerships with eleven organisations in total.

The research consortium was structured initially around six work packages (WP) linked to a range of external partner 'end users' – Figure 1. The timing and nature of the main programme management activities undertaken over the six-year period are presented in Table 1 alongside the dates of the research-on-research (R-on-R) interview data gathering in order to show which activities may have influenced each of the three data points. (Research-on-research - also known as *meta-research*, the *science of science* and *meta-science* - is the study of research itself. It is an evolving discipline that aims to produce evidence on how to improve the efficiency, effectiveness, fairness and impact of research.) Though not a traditional management activity, the systems modelling work is included alongside the main programme management activities due to the link of that sub-team to the wider work of the engineering department that was also leading the R-on-R interview data gathering, and also because the team leading on this work contributed to some of the more foundational management understandings, such as mission-orientation and language development.

The development stage was relatively extensive as it included a three-year initial project, UPSTREAM (2015-2018), that effectively became the pilot project of the larger programme [15], as well as a two-stage bid development over a year period (2018-2019). Once begun, the majority of active management and governance took place between Rounds 1 and 2 of interview data collection (between Oct-Nov 2020 and Feb-Mar 2022). In addition to monthly management team meetings and quarterly full consortium meetings, early activities included: the development of terms of references; the co-writing of the formal programme protocol by the whole team [16]; the co-development of definitions of common terms and a team glossary; and multiple, graphically illustrated presentations and workshops seeking to set out the project vision and foundational understandings. Working with the systems engineers, the aims and objectives were also re-framed using the mission-orientation approach [17].

Towards the end of this period, two Management Team Away Days were scheduled (June and Sept 2021), in response to confusion about the level of autonomy afforded to each workstream lead. This was followed shortly after by an extensive six-month process of intervention integration and identification (Oct – Mar 2022) with a full consortium meeting in April 2022 agreeing the final selection of intervention areas and new sub-teams. Between Rounds 2 and 3 interview data collection (Feb – Mar 2022 to Sept 2023 – Feb 2024), programme management activities continued ongoing, but they became far less common or interventionist.

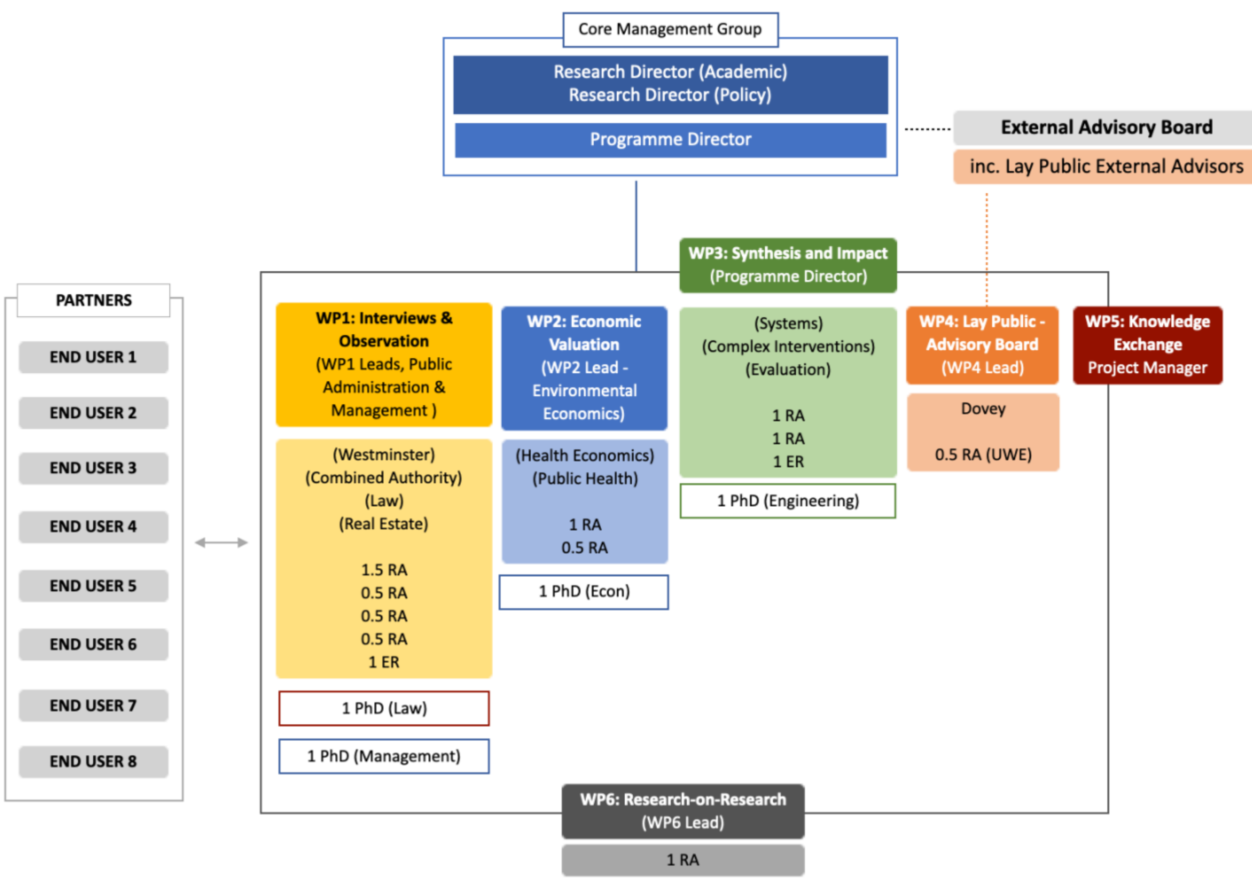


*Figure 1: Team Phase 1 Organogram showing consortium's structure, disciplinary areas and researcher resource with R-on-R (WP6) at bottom.*

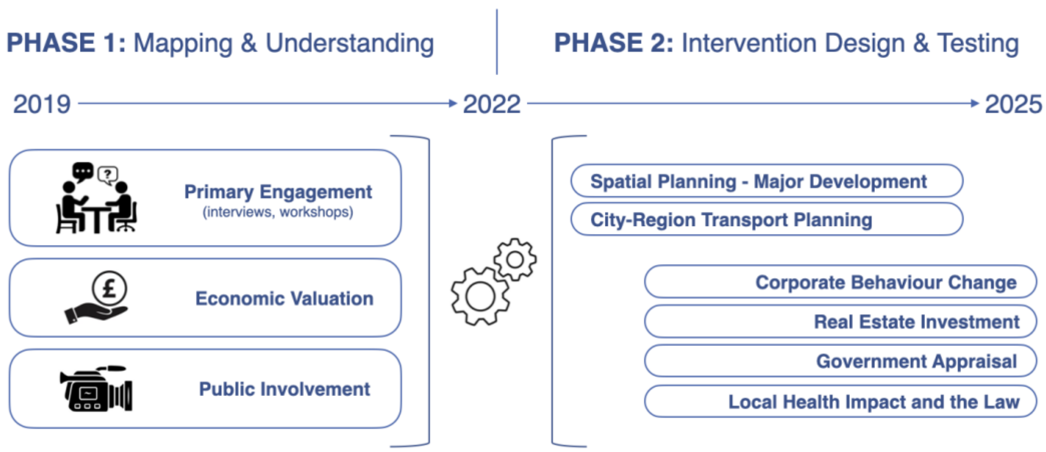


*Figure 2: Simplified graphic of the programme activities over two main phases.*

*Table 1: Timeline of main management activities with research-on-research and systems modelling highlighted.*

| Dates | Activities | Description |
|---|---|---|
| **2015-2019** | *Pilot Project* | *A 3-year pilot project involving a very small number of the core team that followed, it uncovered initial research operationalisation challenges and started process of reflection* [15]. |
| **2018 - 2019** | *Bid development, including graphical illustrations of 'problem space'* | *A 2-stage application process undertaken over the course of a year (2018-2019), it grew to involve most of the programme's research leads.* |
| **Oct 19 – Feb 20** | Early project inception meetings | Involving all members of the consortium, these meetings set out the accepted programme plan alongside lessons from pilot operational challenges and foundational understandings (original theory, TDR working, language). The meetings provided an opportunity to clarify the high-level proposal and to raise questions on specific issues/areas. |
| **Oct 19 – Feb 20** | Terms of Reference (ToR) | These ToR, designed for the research management team, were developed by the Programme Director based on prior issues around clarity of leadership. They were signed off by the Research Director and shared with the research leads, but not used or progressed as a working document so assumed to have limited impact. |
| **Throughout 2020** | Recruitment and induction of wider team / new posts | Recruitment of 15 new researcher posts required most of the first year of operation to complete. It was delayed due to Covid lockdowns and the challenge of recruiting TDR posts (posts that could span multiple disciplines). Some joined early in 2020, others towards the end of 2020. This intermittent recruitment resulted in a stilted induction for new staff. |
| | Co-writing of programme protocol | All research leads and a number of new staff contributed to the writing of a peer-reviewed protocol [16]. This formalised the stage 2 application, enabled greater clarification and shared understandings through the development of new graphical illustrations of the problem space, swim-lane delivery models and the development of a loose, overarching theory of change. |
| **Mar 20 – Mar 21** | COVID-19 | Lock-downs |

| | | |
|---|---|---|
| **Sept 20** | 'Meta-Research' Workshop (Whole Group) | Introducing the aims and objectives of the Research-on-Research workstream to the whole group. |
| **Oct-Nov 20** | R-on-R Interviews | Round 1 |
| **Throughout 20 - 21** | Management and full consortium meetings | Monthly meetings of the work package leads and senior management team. Quarterly full consortium meetings. |
| | Language and definitions | Co-development of team glossaries setting out definitions of main terms causing confusion amongst the group. |
| **Feb 21** | Foundational understandings - paper | Co-development of internal discussion paper involving four research leads and focusing on some of the emerging issues causing confusion including language definitions and operationalisation of TD projects. |
| **Mar 21** | Foundational understandings - briefing | Presentation of theoretical foundations to the group by two research leads responsible for delivery and philosophical foundations of TDR. |
| **Throughout 21** | Intervention Integration Planning and Implementation (WP3 plus WP6) | The programme management and integration team along with the systems engineers spent much of the second year co-developing a range of tools and models to assist in the programme operationalisation, including complex swim-lanes, double diamond and actor constellation mapping. |
| **Jun 21** | Away Day 1 (Management Group) | An independently facilitated day that sought to understand research leads' hopes and drivers, to celebrate success, uncover issues, problem solve and plan any changes. The main issues identified were: clarity of direction, team cohesion, and how decisions are made. |
| **Sept 21** | Away Day 2 (Management Group) | A follow up to Away Day 1 (no independent facilitator) that sought to air any outstanding areas for discussion, clarify our position on key areas, make firm decisions on next steps with specific actions agreed. A main outcome was the placing of two new academic co-leads to lead the integration work package to give more confidence of academic oversight. |
| **Oct – Dec 21** | *Systems Modelling* | *Four systems mapping workshops to communicate and further analyse the complex networks under investigation* |
| **Oct 21 – Mar 22** | Intervention identification | A six-month process of intervention identification, led by the programme integration team working with the systems engineer and public health intervention specialist as well as each of the workstream and intervention area leads. |
| **Jan 22** | Workshop (Wider WP3 Group) | Identifying problem areas: Critical first workshop to narrow the identification of intervention areas. |
| **Mar 22** | Workshop (Wider WP3 group) | Intervention identification: Second workshop to narrow the intervention areas. |
| **Feb – Mar 22** | R-on-R Interviews | Round 2 |
| **April 22** | *Systems Modelling* | *Intervention Selection – Full Consortium (Whole Group)* |
| **May – Oct 22** | *Systems Modelling* | *Development of 7 causal loop diagrams with IA teams* |
| **Feb – Aug 23** | *Systems Modelling* | *Refinement and validation workshop* |
| **Sept 23 – Feb 24** | R-on-R Interviews | Round 3 |

# 3 Methodology

The main steps of the analysis are shown in Figure 3 and are split into two main areas of analysis: i) all vocabulary; ii) (n=245) words identified as transdisciplinary (TDR) language (described in more detail in Section 2.2 below).

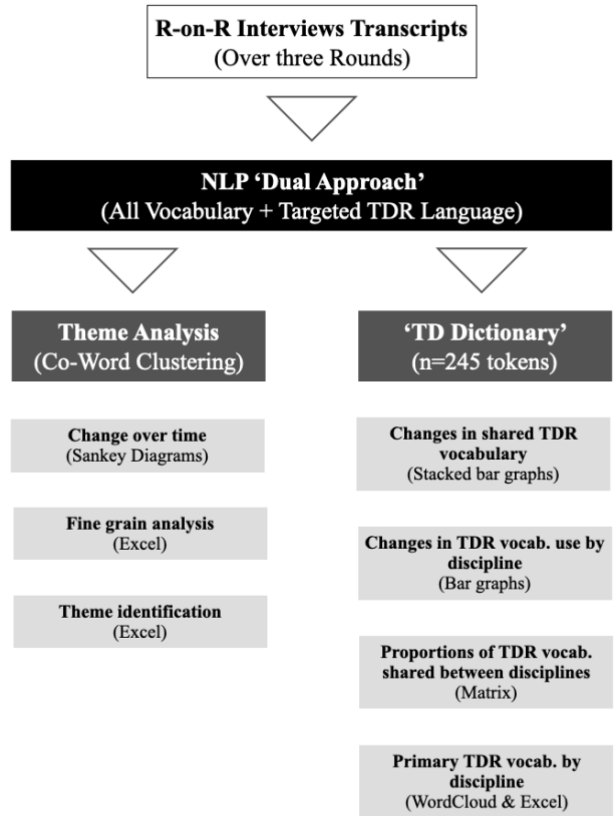


*Figure 3: Flow chart of the main methodological activities.*

## 3.1 Research-on-Research (R-on-R) Interviews

Our approach drew on interview data gathered at three points over the course of the research programme (2019-2025). Hosted within the lead institution's Engineering department, it was undertaken by the consortium's R-on-R sub-team, who operated both within and separately from the main team.

The three rounds of semi-structured interviews were strategically timed to align with key stages of the project in order to elicit participants' perspectives and mental models in a way that is sensitive to the project's evolving context. While the interviews followed a common thematic structure to ensure consistency, they were adapted to reflect the specific phase of the project, allowing participants to contextualize their responses accordingly. Round 1 interviews focused therefore on programme initiation, motivations for joining the research consortium, team formation and anticipated research opportunities and challenges. Round 2 explored the transition from exploratory work to collaborative intervention design, implementation and evaluation of interventions, experiences of systems mapping activities for knowledge integration and deriving lessons when navigating inter/transdisciplinary research challenges. Round 3 interviews focused on the shift towards evaluation of research outputs and outcomes, the communication of research findings, along with reflection on the overall research programme (what worked and what did not work) and moving into a process of programme closure and knowledge transfer. This approach enabled the capturing of rich, representative insights in an inclusive manner while remaining mindful of the practical constraints of time and cost.

Participation included early career researchers, professional service staff (project managers and administrators), co-investigators and research leads in order that the sample was representative of the overall project in a way that a voluntary survey might not be. To date, there remains a paucity of longitudinal studies in the Science of Team Science (SciTS) field that adopt qualitative methodology, despite sustained calls for richer, experiential data on how research teams coordinate knowledge [18, 19]. Existing longitudinal work either spans extended durations with limited attention to the intricacies of specific collaborative processes [20], or employs qualitative data to explore interdisciplinary mechanisms without incorporating a temporal dimension [21].

The research consortium was made up of 13 disciplinary areas, which we split into groups based on their most closely associated UK Research Council: ESRC (Economic and Social Sciences); EPSRC (Engineering and Physical Sciences); and MRC (Medical). We include an additional group (PS), which stands for Professional Services and includes all non-academic posts involved in the research and interviews. As can be seen from Table 2, the large majority of disciplines were from Economic and Social Sciences, while Medical were the lead disciplinary area, and Engineering and Physical Sciences led on the systems science and disciplinary meta-analysis (the subject of this paper). (For brevity, we shorten 'Economic and Social Sciences' to 'Social Sciences', 'Engineering and Physical Sciences' to 'Engineering'; and we exchange 'Medical' to 'Public Health' for accuracy.)

*Table 2: List of researcher academic disciplines categorized by principal UK Research Council Funder*

| UK RC | Disciplines | No. interviews | No. interviews – | No. interviews – |
|---|---|---|---|---|
| **ESRC** | urban development/planning, planning, | 15 (15) | 10 (9) | 10 (6) |
| **EPSRC** | engineering | 3 (3) | 3 (3) | 2 (2) |
| **MRC** | public health | 6 (6) | 5 (4) | 5 (5) |
| **PS** | human resources, professional services | 1 (0) | 2 (2) | 3 (3) |
| | Totals | 25 | 20 | 20 |

*Table 3: List of researcher academic disciplines categorized by principal UK Research Council Funder*

| | | | **Number of Interviews by Discipline** | | | |
|---|---|---|---|---|---|---|
| | **Discipline** | | | **Round 1** | **Round 2** | **Round 3** |
| **disc1** | Urban development/ planning | Social Science | ESRC | | 5 | 3 |
| **disc1a** | Planning | Social Science | ESRC | | 0 | 0 |
| **disc1b** | Urban development | Social Science | ESRC | | 0 | 0 |
| **disc1c** | Real estate | Social Science | ESRC | | 1 | 1 |
| **disc2** | Engineering | Engineering | EPSRC | 3 | 3 | 2 |
| **disc3** | Economics | Economics | ESRC | 3 | 2 | 2 |
| **disc4** | Public health | Public Health | MRC / NIHR | 6 | 4 | 4 |
| **disc5** | Law | Social Science | ESRC | 1 | 0 | 1 |
| **disc6** | Policy studies | Social Science | ESRC | 3 | 0 | 1 |
| **disc7** | Management/governance | Social Science | ESRC | 2 | 1 | 2 |
| **disc8** | Humanities | Social Science | ESRC | 0 | 0 | 1 |
| **disc9** | Human resources | Professional Services | N/A | 0 | 1 | 1 |
| **disc10** | Professional services | | | 1 | 1 | 2 |
| | | | Total | 25 | 18 | 20 |

*Table 4: Interview rounds and timing.*

| **Interview Round** | **No. of Interviewees** | **Interviews Period:** | **Programme Phase:** |
|---|---|---|---|
| **R1** | 25 | Autumn 2020 | Phase 1 (Year 2) |
| **R2** | 18 | Spring 2022 | Transition Phase 1–2 (Year 3) |
| **R3** | 20 | Autumn–Winter 2023– | Phase 2 (Year 5) |

In total, 63 interviews were completed with 39 individuals. Of these, five participants were interviewed in all three rounds, and six participated in two rounds, enabling both longitudinal insight and a diversity of perspectives (see Tables 3-4). One-to-one semi-structured interviews were selected to facilitate reflective discussion on individual practices and to elicit detailed accounts of programme-level structures and processes [22].

Interviews ranged from 26 to 74 minutes duration and followed theme guides covering four core themes: 1) positionality within the project, including levels of involvement with the research and an exploration of motivations; 2) understandings of research mission and clarity of problem definition; 3) the nature of research collaboration and the extent of coproduction within the consortium and with stakeholders; 4) the depth of and nature of knowledge integration attained during the research activities; and 5) the nature of outputs and outcomes being anticipated at each stage in the research process.

### 3.2 Natural Language Processing (NLP)

To deepen the insights generated from these interviews, we apply Natural Language Processing (NLP) techniques to analyse patterns of language use, conceptual alignment, and discourse convergence as indicators of shared understanding. It is proposed that these patterns might serve as proxies for the evolving cognitive and collaborative dynamics within the team. If this is proven to be the case, this integrated approach of data capture and analysis might offer a scalable, data-driven method for evaluating communication processes and knowledge integration in complex, transdisciplinary research environments, and hence help to improve overall performance.

To start with, a list of tokens was created by reviewing all foundational project documentation, including the peer-reviewed project protocol [16], early internal discussion papers and presentations (see Supplementary Material 1). This 'TD Dictionary' included all terms linked to TDR, drawing on earlier paper in this area [15]. These tokens divided into three columns based on their understand of: a) the '*upstream problem'* (n=137 tokens used to describe the upstream systems under investigation in the main research); b) the '*mid-downstream problem'* (n=21 tokens used to describe the built environment and linked socio-environmental and health outcomes) and c) the '*research problem*' (n=84 tokens used to describe the challenge of operationalising the research).

Iterative analyses were then applied to the interview dataset to investigate the evolution of TDR working practice throughout the programme and across the four disciplines involved. The analyses were split into two main areas, with four sub-areas of analysis for the TDR vocabulary:

- Full Transcripts:
  - Theme analysis through co-word clustering (Sankey diagrams and Excel)
- TD Dictionary:
  - Changes in shared TDR vocabulary (stacked bar charts)
  - Changes in TDR vocabulary use by discipline (bar charts)
  - Proportions of TDR vocabulary shared between disciplines (matrix)
  - Primary TDR vocabulary use by discipline (term frequency tables)

This section continues with a description of the pre-processing steps taken that prepared the interview data for analysis followed by a description of each analytical procedure applied.

### *2.2.i Data Pre-Processing*

The transcribed interview data was stored in a series of word documents – one per interview. Metadata pertaining to each interview was stored in an Excel spreadsheet. The metadata entries contained:

- A unique reference code for the interview
- The round that interview was conducted in
- The discipline of the interviewee (i.e., EPSRC, ESRC, MRC, PS)
- A reference to the transcript word document.

A Python script was used to read the metadata entries from the Excel spreadsheet and interview transcripts and collate them into an array of JSON objects with the following schema and text encoded in UTF-8:

```
{
  transcript_id:  string
  transcript_text: string
  all_tokens: string[]
  tokens: string[]
  systems_tokens: { token: string, occurrence: string }[]
  discipline: enum
  round: enum
}
```

The raw text from the transcripts was tokenized, stemmed and stopwords removed. Tokenization extracted all words from the document using regular expression. These were then stemmed using NLTKs PorterStemmer. The stemmed tokens were then compared against a stopword list where matches were removed. The stopword list came from the stop-words python package (https://pypi.org/project/stop-words/).

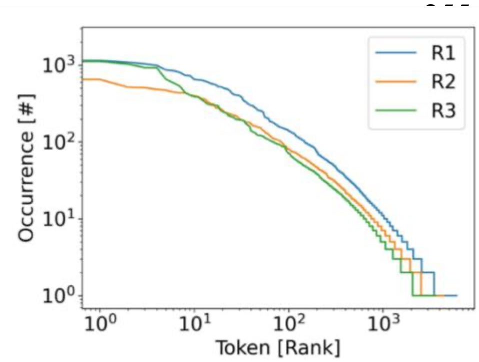


*Figure 4: Distribution of token ranked based on occurrence and plotted on a log-log-scale.*

Figure 2. shows the occurrence distribution of tokens across the interviews based on round and shows the typical log distribution one would expect from interview data where there is a vocabulary that is used by many, which then suddenly tails with tokens that are used only a few times. The tokens were then checked against the TDR vocabulary tokens and matches and occurrences were recorded for subsequent analysis. With the pre-processing complete, the analysis turned to evaluating different types of NLP analysis and how they may bring some insight into the use of systems thinking terminology across a transdisciplinary project.

***3.2.1 Co-occurrence of TDR across disciplines:*** The co-occurrence of TDR vocabulary was thought to be of interest because it represents common (shared) lexicons as well as isolated lexicons (not shared). Co-occurrence matrices were used to assess the degree of co-occurrence. The matrices detailed the number of TDR tokens used by one discipline were also used by another discipline. These were directed matrices where "terms used by A are in B" and "terms used by B are in A" are not equivalent due to the different vocabularies used by the disciplines. It was proposed that these matrices would give an insight into the degree of cohesion between disciplines.

**3.2.2** ***TDR vocabulary over time:*** Evaluating vocabulary over time was of interest to examine how the vocabulary of individuals and groups evolve overtime through the project phases and an aggregate level to establish convergence on a shared vocabulary, as well as identifying vocabulary that is redundant or no longer used. This was achieved by plotting the interviews by round and discipline and then within these groups checking how much of the TDR vocabulary was present within their respective token sets. The was plotted as a bar chart with the anticipation that it would be able to reveal the level of engagement with the systems thinking vocabulary over time.

**3.2.3** ***Term Frequency:*** Term Frequency Tables of the TDR terminology used by each of the disciplines were also produced initially to provide WordClouds, though these were ultimately discarded following multiple iterations, which meant they didn't align to the Term Frequency Tables. Use of TDR vocabulary across whole programme was compared against those used in Round 3, and terms were also disaggregated into their three areas: 'upstream problem', mid-downstream problem' and 'research problem'.

#### *3.2.4* Theme Analysis

Analysing the themes used were of interest because it is possible to examine the relative attentions to aspects of the programme. Such meso-level analysis (Wasiak et al) is necessary to provide meaningful contextualization of specific utterances of vocabulary within the context of the project and to enable analysis by topic rather than individual tokens (words).

Emerging themes were identified using co-word clustering and labeled through a series of workshops involving individuals that had worked on the project. A network was created where tokens were assigned to a node and edges defined the degree of co-occurrence within the interview. Each interview transcript token set was iterated through and a look-ahead distance, $d$, was used to denote that two terms co-occurred within the same passage of text and the weight of the edge in the network was incremented accordingly. A token was only considered once within each look-ahead window. Windowing a transcripts token set in this fashion enables the generated network to draw out themes that were present in different sections (e.g., answers to different questions). The edge weightings were then normalized to account for variations in token frequency:

$$n_{i,j} = \frac{w_{i,j}}{(f_i + f_j - 1)} \qquad (1)$$

Where $n_{i,j}$ is the normalised edge weighting and is determined by the number of times $i$ and $j$ have co-occurred ($w_{i,j}$) divided by the number of co-occurrences that could have occurred ($_i + f_j - 1$). Themes were then identified using the Louvain partitioning algorithm (Blondel et al. 2008). The algorithm works by allocating terms to partitions with the objective of returning a partition set that produces the highest modularity score for the graph. Modularity ($Q$) is an assessment of the quality of the matrix partition and is defined as (Newman 2004):

$$Q = \frac{1}{2m} \sum_{i,j} \left[ A_{i,j} - \frac{k_i k_j}{2m} \right] \delta(c_i, c_j) \qquad (2)$$

Where $m=1/2\sum A_{i,j}$ and is the number of co-occurrences within the graph. $\delta$ is the Kronecker delta function and is 1 if a co-occurrence exists between two terms and 0 otherwise. $k_i k_j/2m$ is the probability that a co-occurrence may exist between two terms, where $k_i$ is the number of terms that have co-occurrences with term $i$, and $k_j$ is the number of terms that have co-occurrences with term $j$. And, $A_{i,j}$ is the weighted co-occurrence between two terms in the graph. To start, the algorithm assigns each node to its own partition. The algorithm sequentially moves one node to a different partition and calculates the change in $Q$ (Equation 3).

$$\Delta Q = \left[\frac{p_{in} + k_{i,in}}{2m} - \left(\frac{p_{out} + k_i}{2m}\right)^2\right] - \left[\frac{p_{in}}{2m} - \left(\frac{p_{tot}}{2m}\right)^2 - \left(\frac{k_i}{2m}\right)^2\right] \quad (3)$$

Where $P_{in}$ is sum of all the normalised co-occurrence weights within the partition that term $i$ is being included in, $P_{tot}$ is the sum of all the normalised co-occurrence weights to term within the partition that $i$ is being included in, $k_i$ is the co-occurrence degree of $i$, $k_i$, in is the sum of the normalised co-occurrence weights $i$ and other terms within the partition that $i$ is merging with. From this, $\Delta Q_{max}$ can be identified. The associated terms are then assigned to the same partition, and the algorithm repeats the previous step of identifying the next term movement that will result in a further increase in modularity. If no further movement of terms achieves an increase in modularity, the algorithm terminates resulting in the partition set that gives the highest modularity score. This iterative process results in a partition set that are highly connected internally and weakly connected to one another. Hence, it is a form of hierarchical clustering, and the algorithm iterates until the modularity can no longer be increased by further aggregation of the terms.

A threshold of >5 was used to select the clusters to be taken forward for discussion with the individuals involved in the project to determine a theme title and description. It was anticipated that this analysis would be able to generate meaningful theme that the individuals could recognize and relate to in the context of the transdisciplinary project. The theme analysis was performed using the Python NetworkX library.

Plots were then produced showing the occurrence of theme tokens across the interview rounds and across the different interviews. It was anticipated that different themes would emerge, grow and decline between rounds indicating changes in the project's activities.

# 4 Results & Interpretations

The following results are split into two main sections of description and interpretive analysis. First, we present the clusters (themes) generated by NLP of all vocabulary used over time. Then, we analyse a range of 245 TDR tokens (described in Section 2), and we consider their usage over time and by discipline.

## 4.1 Evaluation of all vocabulary (co-word clustering into themes)

The co-word clustering produced 11 groups of linked tokens, of which two we combined due to a high degree of thematic overlap, and one was removed (8 in Table 5 below) due to lack of discernable theme, with nine therefore remaining numbered 1-7, 9-10 (Figures 5 and 6). For the purposes of the analysis we use the following descriptions for each of the ranges of occurrence and percentage of interviews (0-100 / <30% = Very Low; 100-200 / 30-40% = Low; 200 – 500 / 40-80% = Moderate; 600 -700 / 80-90% = High; 700 – 800 / 90-100% = Very High). Each theme was given an initial one-word title, which was then adjusted to a more accurate phrase describing each theme (Table 5).

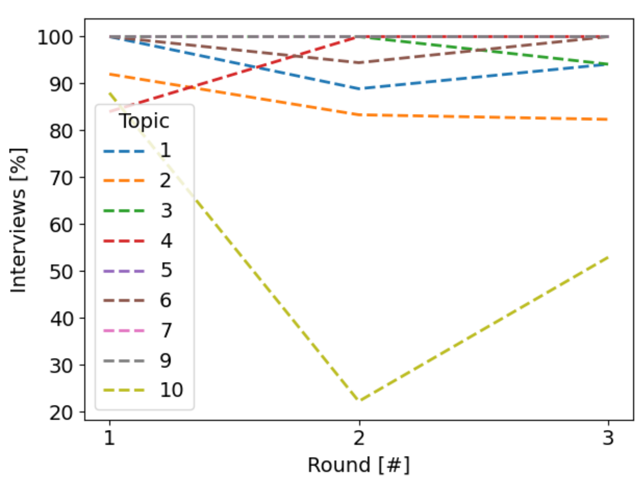


*Figure 5: Interview % is the number of interviews in Round X that cover that theme.*

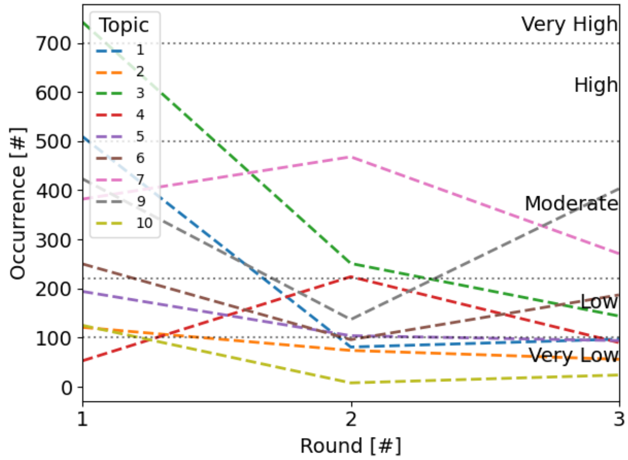


*Figure 6: Line chart showing number of times (occurrence) the theme has been discussed overall.*

| Key No. | Initial theme title | Final theme description |
|---|---|---|
| **1** | differences | New, large-scale research approaches for real world problems |
| **2** | governance | Local government case studies |
| **3** | health | Health, environment & decision-making |
| **4** | mission | Mission and review of integration |
| **5** | networks | New shared understandings |
| **6** | opportunity | Many different people and perspectives |
| **7** | project | Project structure, phasing and timelines |
| ***(8)*** | *reflection* | *N/A [Removed]* |
| **9** | stakeholders | Collaboration in research |
| **10** | urban | Urban development systems |

*Table 5: Table showing initial theme titles alongside final theme description*

***(1) New, large-scale research approaches for real world problems:*** Tokens in this theme include: '*different way / ways*', '*different research*', '*different interpretations*', '*transdisciplinary research*', '*different understandings*' and '*different definitions*', as well as '*real world*' and '*world problems*' (or 'real world problems'). This theme appears in a very high percentage of interviews throughout the research programme, but the level of occurrence drops sharply after Round 1 from high to very low. The funders asked explicitly for '*new approaches to population health research*' [23, p.3], so it is unsurprising that this appears to be a theme discussed throughout, though the notable drop in occurrence after Round 1 suggests that the majority of the team did not preoccupy themselves with this more 'meta' challenge after the programme got underway, or otherwise that it became less relevant over time. This makes sense given that Phase 1 required considerable attention to this area, as the team was newly forming and working as a whole group, whereas by Phase 2 the consortium was established and had split into more manageable sub-teams.

***(2) Local government authority case studies:*** Tokens in this theme include: '*local authorities*', '*combined authority*', '*case study*', '*case studies*'. The research programme had two initial local government case studies: one spatial plan for a large property development and another strategic plan on city-region transport planning. This theme appears in a very high then high percentage of interviews across the programme, but the occurrence started low and decreased to very low. It makes sense that there is a considerable disparity between percentage of interviews (very high - high) and occurrence (low - very low) as only two of the seven intervention areas were focused on local government case studies, but they linked in a limited way to all. That the occurrence and percentage of interviews decreases over time also makes sense as these two case studies started at the beginning of the programme while the five other intervention areas only started in Phase 2.

***(3) Health, Environment and Decision-Making:*** Tokens in this theme include: '*decision-makers*', '*policy makers*', '*health impact*', '*making decisions*', '*cost benefit*', '*planetary health*', '*world problems*', '*evidence base*', '*literature reviews*'. This theme is present in a very high percentage of interviews throughout (albeit with a slight drop in Round 3) and it occurs a very high number of times in Round 1, though this drops to moderate then low in Rounds 2 and 3. This theme represents the main area of focus of the research programme so it's unsurprising that it features in a very high number of interviews throughout, or that there was such a high number of occurrences at the start. The sharp drop in occurrence (to moderate then low) in Rounds 2 and 3 may be due to the operationalisation challenges of Round 1 and the increased familiarization with this 'meta' challenge space (which the R-on-R interviews focused people's attention on).

***(4) Mission and review of integration:*** Tokens in this theme include: '*first question*', '*first theme*', '*researchers relationship*', '*way forward*', '*six months*', '*improve integration*', '*truud mission*'. It appears as high (Round 1) then very high (Rounds 2 and 3) percentage of interviews, whereas occurrence is very low in Round 1, moderate in Round 2 and very low again in Round 3. This suggests that while mission-orientation and evaluation of group working was a theme of interest across the consortium throughout the programme, it was not a substantial one (or not considered much by all), especially at the beginning and end of the programme. This makes sense given that: a) the consortium was new to the language of mission-orientation at the start; b) by the end of the programme the consortium was less concerned with the mechanics of the research operationalisation; c) the concept of mission-orientation had been introduced to the group between Rounds 1 and 2.

***(5) New shared understandings:*** Description: Tokens in theme include: '*shared understanding*', '*shared language*', '*working together*', '*never worked*', '*completely different*', '*package six*' (the research-on-research work package). This theme was covered in in every interview (100%) and over every round, but only a low amount and this reduced to very low in Rounds 2 and 3. As with theme (1) this suggests that the relevance of this subject to the group dropped after Round 1, and was not a high priority generally. That it was covered is not surprising given it is the focus of the R-on-R interviews.

***(6) Many different people and perspectives:*** Tokens in this theme include: '*various different*', '*bringing together*', '*different areas*', '*different people*', '*coming together*', '*different perspectives*', '*different backgrounds*'. This theme appears in a very high percentage of interviews throughout, though only a moderate level of occurrences in Round 1, and this decreases to very low in Round 2 before increasing to low in Round 3. As with some of the themes above, this theme is discussed across the group, but only a moderate to low amount, with very little attention on it in the middle of the programme. This may be explained by the fact that we spoke a good deal at the beginning of the project on the challenge of large-scale transdisciplinary working, but it was only really some of the core management team who were deeply involved in this particular challenge area. The slight increase in interest towards the end of the programme may be due to the team reflecting on the challenges overall.

***(7) Project structure, phasing and timelines:*** Tokens in this theme include: '*two years*', '*phase two*', '*work package*', '*consortium meetings*', '*data collection*', '*different aspects*', '*qualitative research*', '*package two*'. As with theme (5), this theme was covered in in every interview (100%) and over every round. However, the number of times it was discussed was moderate, with a slight increase in Round 2 (almost to 'high'), following by a sharp reduction in Round 3, though still within the 'moderate' range. This makes sense as this theme would have been a core concern for all members of the consortium, and especially in Round 2. The pressure in terms of timelines and project structure as we approached the end would have dropped off as the uncertainties reduced.

***(9) Collaboration in research:*** Tokens in this theme include: '*work together*', '*different approaches*', '*come together*', '*working across*', '*people within*', '*different disciplines*'. This theme appears in all interviews throughout the programme, but while it occurs a moderate amount at the beginning and end, it drops sharply (to low) in Round 2. As with the other themes, this theme is also discussed across the group throughout, but its level of occurrence is distinct given the sharp drop in Round 2. One explanation could be that the Round 2 interviews took place after Phase 1 had completed and Phase 2 had been agreed, thereby lessening the need for attention to this theme.

***(10) Urban development systems:*** This theme includes tokens such as: '*systems approach*', '*real estate*', '*private sector*', '*local government*' and '*urban planning*'. The percentage of interviews in this theme across the three rounds is markedly different from all others: Round 1 starts high, but drops sharply to very low in Round 2 before increasing back up again to moderate in Round 3. Occurrence on the other hand starts low in Round 1 then reduces to very low in Rounds 2 and 3. This theme is sufficiently similar to theme 3 (health, environment and decision-making) to warrant their integration, but we have kept them separate due to the difference in their data profiles. We say in theme 3 that there was a sharp decrease in the occurrence in Round 2, which may help explain the sharp reduction in percentage of interviews in this theme: i.e. it may be due to the operationalisation challenges of Round 1 and the increased familiarization with this 'meta' challenge space, thereby taking the group's attention away from the main research area (of urban development systems).

## *4.2* Evaluation of *TDR vocabulary*

### *4.2.1* *Changes in shared TDR vocabulary*

The following analysis focused on the 'TD dictionary' of 245 tokens (see section 2.ii above). For this analysis we use the following ranges: 0-50 = Very Low; 50-100 = Low; 100 – 150 = Moderate; 150 - 200 = High; 200 – 250 = Very High.

Figure 4 shows the proportion of TDR vocabulary used over time by the number of disciplines that use it (i.e. vocabulary that is shared between disciplines). In Round 1, almost half of the TDR vocabulary (moderate) is not used by any of the disciplines, and that proportion increases relatively significantly over time (albeit remaining within the moderate range). Over half of the TDR vocabulary (also moderate) is used collectively by 1, 2 or 3 of the disciplines (not all 4), but that too decreases substantially over time (also remaining moderate). A very low proportion of the TDR vocabulary is used by all four disciplines in Rounds 2 and 3. Overall, the trend is of reducing use of TDR vocabulary, albeit with wider uptake and moving, potentially, towards convergence. These results

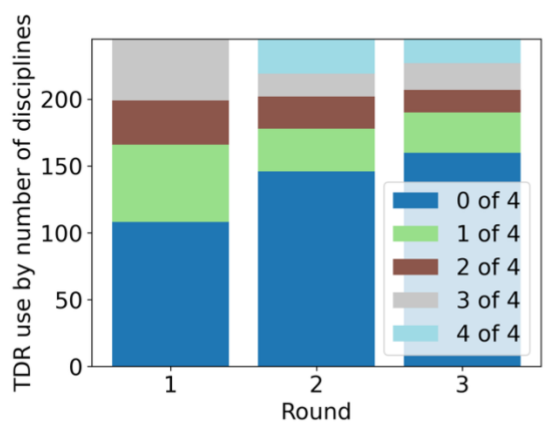


*Figure 7: Stacked bar chart of the use of the TDR vocabulary over time by number of disciplines.*

suggest that much of the TDR vocabulary is either unfamiliar or not relevant to the questions and discussions posed by the interviews for any discipline. This is arguably unsurprising for those in economic and social, public health and professional services given it's not an area of specialism, though it is for the engineers, which suggests there is a considerable amount of jargon that may not be useful. Conversely, these graphs suggest that there are 135 words that used by at least one or more of the disciplines (40 words used by all four disciplines; 20 used by three; 33 by two; and 42 by one). Overall, this chart suggests a natural convergence across the disciplines as a low proportion of useful vocabulary becomes shared and more familiar.

### *3.2.ii Changes in use of TDR vocabulary by discipline*

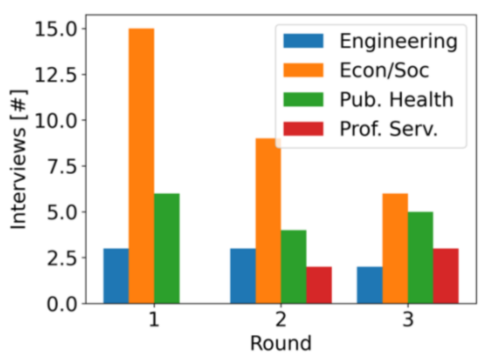


*Figure 8: Bar graph showing number of interviews within which each discipline used TDR vocabulary.*

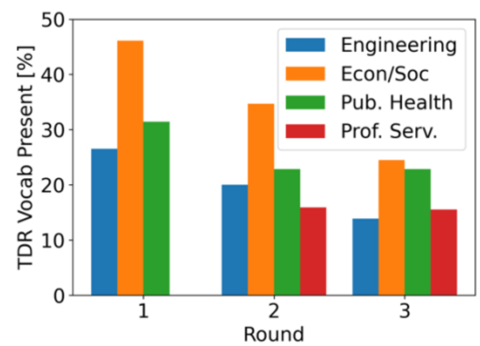


*Figure 9: Bar graph showing percentage of TDR vocabulary used by different disciplines over time.*

Figures 5 and 6 show the number of interviews (left) and the percentage of TDR vocabulary (right) used by each discipline as it changes over time. The academic researchers (economic and social, public health and engineering) all followed a broadly similar trajectory over time, reducing the amount of TDR vocabulary they used. In contrast, the professional services team did not use any TDR vocabulary in the first round, although they did in Rounds 2 and 3, and while in fewer interviews, they used a similar proportion of the TDR vocabulary as the academic disciplines. Notably, at the start of the project, the economic and social scientists used the greatest diversity of TDR vocabulary across by far the widest range of interviews, though this reduced substantially over time to a level similar to the other areas (45% across 15 interviews in the first round, 30% in the second across 8 interviews, and 23% in the third across 6 interviews). Overall, the decreases in academic usage and increases in usage by professional services suggest a potential trajectory across the consortium as a whole towards convergence of shared TDR vocabulary of between 15-25%. As with the stacked bar chart showing number of disciplines (Figure 4), these results suggest that while a majority of the TDR vocabulary becomes less relevant over time, a significant, if small proportion of the TDR vocabulary is used and useful, becoming more familiar to professional service staff as well, and there is a natural convergence across the consortium.

#### *4.2.2* **Proportion *of TDR vocabulary shared between disciplines***

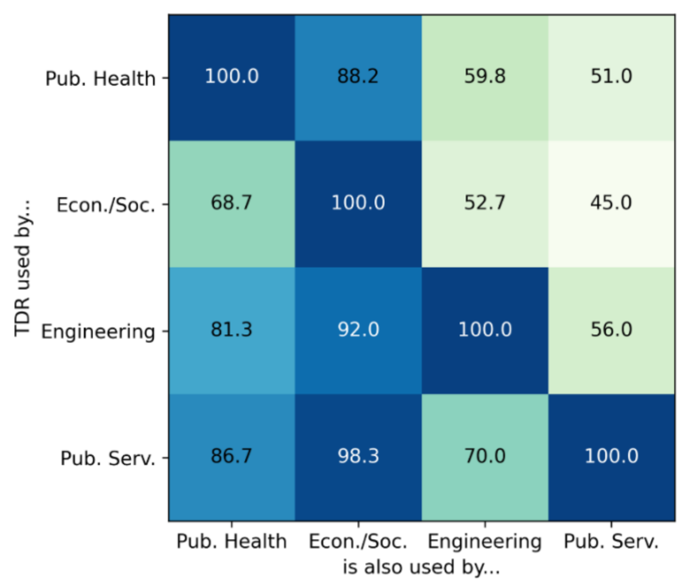


*Figure 10: Matrix showing the proportion of TDR vocabulary used in one disciplinary area by another.*

*Table 5: Table showing the proportion of TDR vocabulary used in one disciplinary area by another.*

| Economic and Social used: | Public Health used: |
|---|---|

| | |
|---|---|
| • 98.3% of Professional Services<br>• 92% of Engineering<br>• 88.2% of Public Health | • 86.7% of Professional Services<br>• 81.3% of Engineering<br>• 68.7% of Social and Economics |
| Engineering used: | Professional Services used: |
| • 70.0% of Professional Services<br>• 52.7% of Social and Economics<br>• 51.0% of Public Health | • 56.0% of Engineering<br>• 51.0% of Public Health<br>• 45.0% of Social and Economics |

Based on the words we assigned as being TDR language (Supplementary Material 1), these data (Figure 7 and Table 5) shows that the economic and social scientists appeared to use the most TDR language overall, then public health researchers, then engineers, and professional services used the least. Notably, the social scientists and the public health researchers used far more TDR vocabulary than the professional services and engineering researchers. That the professional services staff did not use much TDR vocabulary is arguably unsurprising (and would echo the findings above in 3.2.b), but this does not explain the disparity with the engineers. One explanation could be that the engineers were focused primarily, particularly in Phase 1, on the research-on-research work package (and more process-oriented systems analysis), rather than the wider research focal areas more broadly. Another could be that the engineers did use TDR language, but, being most familiar with it, used a different vocabulary to those newer to the area. It also suggests that the social science and public health researchers, though new to the area, picked up the language very quickly and prioritized its usage.

#### 4.2.3 **Primary *TDR vocabulary by disciplinary area – Term Frequency and manual analysis***

Of the top ten words used in each discipline in total across the whole programme, those used by all four disciplines were: *systems*, *discipline*, *impact* and *outcome*. *Integrated* and *mission* were used by three of the disciplines. Two disciplines used seven of those words: *transdisciplinary*, *stakeholders*, *policy*, *upstream*, *actors, resource* and *influence*. The four remaining words – *aim*, *valuation*, *engagement* and *complex* - were used by only one discipline. Of the top ten words used in each discipline in the final round, those used by all four disciplines were: *integration (or integrated)*, *impact* and *stakeholder*. Those used by three of the disciplines were: *systems*, *discipline*, *mission* and *engagement*. All the other words were used by just one discipline: *timescales, transdisciplinary, interdisciplinary, influence, risk, policy, upstream, valuation, involvement, communications, influence, outcome, resource, reflection, complex, institution*.

*Table 6: Top 10 most commonly used TDR tokens by disciplinary area across whole programme divided into TDR vocabulary type (U) Upstream problem, (M) Mid-Downstream problem, (R) Research problem.*

| | **Engineering** | | **Econ. and Social** | | **Pub. Health** | | **Prof Services** | |
|---|---|---|---|---|---|---|---|---|
| | systems (R) | 8 | discipline (R) | 28 | impact (M) | 14 | stakeholders (R) | 5 |
| | discipline (R) | 8 | policy (U) | 25 | discipline (R) | 14 | mission (R) | 5 |
| | integrated (R) | 7 | impact (M) | 24 | upstream (U) | 12 | integration (R) | 4 |
| | impact (M) | 7 | systems (R) | 23 | policy (U) | 11 | influence (U) | 3 |
| | complex R) | 7 | upstream (U) | 22 | mission (R) | 11 | outcome (U) | 3 |
| | transdisciplin. (R) | 6 | outcome (U) | 22 | integration (R) | 10 | impact (M) | 3 |
| | stakeholders (U) | 6 | transdisciplin. (R) | 22 | outcome (U) | 9 | systems (R) | 3 |
| | outcome (U) | 6 | resource (R) | 21 | systems (R) | 9 | engagement (R) | 3 |
| | mission (R) | 6 | aim (R) | 20 | valuation (U) | 8 | discipline (R) | 3 |
| | actors (U) | 6 | influence (U) | 19 | actors (U) | 8 | resource (R) | 3 |
| **Upstream** | 3 | | 4 | | 5 | | 2 | |
| **Mid-downstream** | 1 | | 1 | | 1 | | 1 | |
| **Research** | 6 | | 5 | | 4 | | 7 | |

*Table 7: Top 10 tokens used by discipline in Round 3 divided into TDR vocabulary type: (U) Upstream problem, (M) Mid-Downstream problem, (R) Research problem.*

| | **Engineering** | | **Econ. & Social** | | **Pub. Health** | | **Prof Services** | |
|---|---|---|---|---|---|---|---|---|
| | systems (R) | 2 | stakeholders (U) | 6 | impact (M) | 5 | stakeholders (U) | 3 |
| | discipline (R) | 2 | integration (R) | 6 | discipline (R) | 5 | mission (R) | 3 |
| | integrated (R) | 2 | discipline (R) | 5 | mission (R) | 5 | communications (R) | 3 |
| | impact (M) | 2 | transdisciplin. (R) | 5 | integration (R) | 5 | integration (R) | 2 |
| | stakeholders (U) | 2 | interdisciplin. (R) | 5 | stakeholders (U) | 5 | influence (U) | 2 |
| | mission (R) | 2 | systems (R) | 4 | policy (U) | 4 | outcome (U) | 2 |
| | reflection (R) | 2 | influence (U) | 4 | upstream (U) | 3 | impact (M) | 2 |
| | engagement (R) | 2 | engagement (R) | 4 | valuation (U) | 3 | systems (R) | 2 |
| | timescales (R) | 2 | risk (R) | 4 | involvement (R) | 3 | engagement (R) | 2 |
| | complex (R) | 2 | impact (M) | 3 | institution (U) | 3 | resource (R) | 2 |
| **Upstream** | 1 | | 2 | | 5 | | 3 | |
| **Mid-Downstream** | 1 | | 1 | | 1 | | 1 | |
| **Research** | 8 | | 7 | | 4 | | 6 | |

*Table 8: Words used by at least three of the disciplines over whole programme and in the final round, and whether they're from the 'upstream problem', 'mid-downstream problem' or 'research problem'.*

| Vocabulary | TDR tokens used by 3-4 disciplines over whole programme | TDR tokens used by 3-4 disciplines in Round 3 |
|---|---|---|
| **Upstream problem** | *outcome* | *outcome, stakeholder* |
| **Mid-downstream problem** | *impact* | *impact* |
| **Research problem** | *systems, discipline, integration (or integrated), mission* | *systems, discipline, integration (or integrated), mission, engagement* |

Perhaps the most obvious aspect of Tables 7-9 is the similarity of the most common words used across all four disciplinary areas. The vast majority are either from the 'research problem' space (e.g. '*systems*', '*complex*', '*integration*') or are words from the other problem spaces that could also fit within that research problem space (e.g. '*stakeholders*' '*policy*', '*impact*'). In the TD dictionary (see Supplementary Material 1), there are many context-specific words that were commonly used in the programme (e.g. '*cost-benefit'*, '*land*', '*public realm'*, '*health inequalities'*, '*deprivation*'). It is tempting to draw a conclusion that this infers a move towards convergence of language. However, a simple explanation for this is that the R-on-R interviews were focusing on the research problem space so in reality this reveals very little. Notably, the Public Health researchers appeared to use more vocabulary from the upstream problem area than the others (e.g. '*valuation*', '*institution*'), though this seems too small a number to draw any significant conclusions against. Comparing Round 3 by vocabulary 'type' (upstream, mid-downstream or research problem area) against vocabulary used across the programme as a whole (Tables 7-8) suggests that there may have been a convergence between the Engineering and Economic and Social Science researchers focused more on the research problem towards the end of the programme than the Public Health and Professional Service staff. It also shows just how little any of them focused on the mid-downstream and relatively much less on the upstream and mid-downstream problems. It is notable too that, while all used the term '*systems*', only the Economic and Social Scientists (and Engineers) had the word '*transdisciplinary*' in their top 10. Referring to the TD Dictionary, we can see that the Public Health team did in fact use both ‘*interdisciplinary*’ and ‘*transdisciplinary*’, but the Professional Services staff didn’t use them at all – perhaps it was overly jargonistic.

# 5 Discussion

In starting to think about the evaluation of TD working (and the potential for NLP to assist with that) we felt there were some reasonable expectations: firstly, that the language of TDR might be more widely adopted over time; secondly, that researchers might revert to type (doing what they did previously); and thirdly, that there was likely to be a fairly stable lexicon. These assumptions, based on past experience [15], led us to the two main outcomes and three objectives set out in the introduction: i.e. in summary, what can we learn from analysing these interviews using language analysis, both with regards TD learning as well as the application of NLP, and specifically in terms of: changes in language usage, commonality and variance. We were also interested in whether R-on-R might provide a rapid response, and whether this NLP approach might be scalable and reproducible.

## 5.1 Improvements to TD working – learnings from themed analysis

The themes identified through co-word clustering using NLP (3.1) offer a number of potential lessons, the strengths and limitations of which are discussed below. There are two themes that increased markedly between Rounds 1 and 2 - (4) '*mission, review of integration*' and (7) '*project structure, phasing and timelines*') - and there are two separate themes that decreased markedly over the same period - (6) '*many different people and perspectives*' and (9) '*collaboration in research*'. This makes sense in that: firstly, the group started out aware of the challenges in an abstract sense (i.e. that there were many different disciplines to be integrated and they needed to collaborate), which became less relevant after Round 2 as the team split into their various autonomous sub-groups; and secondly, they may well have become more familiar with the language of TD working and mission-orientation, and the practicalities in terms of delivery. It also supports the above conclusion that the management activity (or at least the experiences gained between Round 1 and Round 2) helped develop the team in terms of their shared understandings.

## 5.2 Improvements to TD working – learnings from analysing TDR vocabulary

*Table 9: List of jargon from key texts never used once*

| |
|---|
| cognitive artefact |
| complex adaptive systems |
| complex inter-linkages |
| consumption-based growth |
| critical awareness |
| critical reflection |
| end users |
| endogneous variables |
| exogenous variables |
| externalities |
| group cognition |
| policy-implementation gap |
| practitioner-researcher integration |
| profiteering |
| wicked problems |

There are (at least) two main possible conclusions to be drawn from the analysis of the TDR vocabulary, and specifically the apparent reduction and convergence of lexicon over time (Sections 3.2.i-ii and Figures 7-9), conclusions that appear largely supported by the Term Frequency Tables and manual analysis (Section 3.2.iv, Figs 11-14 and Tables 6-8). Firstly, it suggests that it took much of the six years to develop a shared language; and secondly, that, ultimately, the vocabulary required is likely far less than might be expected (i.e. the less jargon the better), 75-85% of which were not used (169-205). To illustrate this, Table 9 shows 15 words from key texts [24], which were never used in any of the interviews. The time aspect is expected: it took the consortium six months of considerable discussion just to agree the meaning of the word 'health' [25]. However, this does have implications for research design and funding in terms of the resourcing and development of new inter- and transdisciplinary teams, especially larger teams. It may well be that this process cannot be easily short-cut: it's more a matter of exposure, and factoring in time for the development of shared understandings and reframing [1]. That said, managing expectations is critical, so teams being made aware of these processes in advance will likely help ease the process [2, 24, 26]. Looking at the management activity (Table 2) in this context is also potentially revealing in that a considerable amount of work was done in those early stages (e.g. co-development of a glossary, mission-orientation, development of foundational understandings), which may have accelerated that convergence, but may also have been seeking to fast-track a process that was not able to be forced.

### 5.4 Potential use of NLP – Limitations & Suggested Improvements

While the NLP analysis suggests some useful findings as set out above, improvements to the process should be developed based on the following limitations.

- *Interpretations of the TDR vocabulary*: while this exercise has been undertaken by the lead author in close discussions with the co-authorship team who together have a relatively broad and deep understanding of the operationalisation of the programme, all interpretations are based on authors' opinion and it has not been possible to validate the findings through additional engagement with the research consortium.
- *Themed analysis* (co-word clustering): while some themes appeared relatively robust in the coherence of tokens (see Supplementary Material 2 and 3), others did not appear to offer clear or coherent themes, especially those with a low number of tokens – e.g. (10) 'urban development systems' - and hence why we decided to remove one titled 'Reflection'.
- *Variations in quantum*: there were large variations in both the number of disciplinary areas represented and in the number of tokens in each theme. While we are not looking for statistical significance, there remains a clear issue that these variations may sway the results.
- *Interviewer words* were included as the data was perceived to be conversational between team members, rather than a standard interviewee. However, it may be that in the analysis, the inclusion of the questions may have skewed the results. If attempted again, analysis should look at data with and without interviewee vocabulary to assess any difference.
- *Programme developments:* There were substantial changes across the programme, both in terms of who the consortium operated, but also the questions asked in the R-on-R interviews (see Supplementary Material 4). For example, only Round 1 asked about shared terms, and there was more variance in the interview questions in Round 1 compared to Rounds 2-3. Phase 1 and Phase

2 were also markedly different: the level of collaboration in Phase 1 was higher across the whole consortium, while in Phase 2 the focus was on the sub-teams and collaboration between certain sub-teams. It is arguably therefore unrealistic to expect that putting all the data together would show more synergy, and it would therefore make more sense to look at this by phases.

- *Normalisation and threshold determination:* These were non-trivial challenges. The NLP analysis required us to focus on disciplinary (research council) groupings instead of observing the data as a whole, which did not allow for imbalances in group numbers. The use of thresholds instead of normalisation was discussed, but eventually discarded given that the exercise was to test broad changes over time.

To achieve higher confidence in these approaches to NLP analysis would therefore require validation, ideally from the interview participants, or some other form of triangulation, perhaps with others undertaking qualitative analysis of these data. With regards the themed analysis, setting thresholds in terms of token numbers and/or coherence appears essential. With regards the more targeted TDR analysis, this appeared potentially useful in terms of revealing the words most commonly used as part of a functional ‘TD Dictionary’. An additional challenge may be the length of time it has taken to develop this approach, though this should be substantially reduced in future following familiarisation.

NLP can clearly show us patterns, but a question remains unanswered as to what optimal data should look like for the analysis to be robust. For example, should all interview questions be the same across interview rounds? Should there be comparison across the interview rounds? Should the interviewers words be cleansed? Is there a danger that words used by senior leads/researchers were replicated by participants without understanding or further integration? In qualitative research, the meaning is usually derived from reading a full transcript and doing constant comparison of codes/themes during qualitative analysis.

Overall, it is questionable whether NLP - in the way that it has been used in this paper and with this dataset - is able to answer the three outcomes set in the paper. The data does not seem to show clear patterns to suggest "*evolving cognitive and collaborative dynamics within the team*" (as suggested in the methodology). That said, the paper does suggest that if the data is formatted in the appropriate manner, NLP can bring forth perspectives that could otherwise be missed in qualitative analysis. The semi-automated nature of NLP also means that there is less risk of researcher bias. Addressing the gaps identified in this paper may help us to understand the potential for NLP to support rapid research-on-research feedback in the creation of just and sustainable futures for all.

## Acknowledgments

We are grateful to, and acknowledge the work of Dr Eli Hatleskog and Dr Stephanie Briers who effected the three rounds of qualitative data collection through interviewing, transcription and anonymisation of these data. We are also grateful to the research participants for their time and contribution as interviewees.

## Supplementary Material:

- Topic Guide and Interview Qus
- TD Dictionary
- Tokens Assessment

## References

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