Decision Making under Uncertainty and Complexity - Bringing Morphological Analysis Out of The Shadows and into the Future.

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Abstract. The rather complicated-sounding term Morphological Analysis (MA) is a particularly useful, albeit hidden, method for helping to structure problems and support decision making, notably when they are complex, "wicked" and inherently contain high levels of uncertainty. It has also been called "totality research", an "idea factory", and "strategic options analysis". Although introduced in its generalised form some 70 years ago it has lingered in the deeper recesses of the OR toolkit.

Morphological analysis (MA) systematically structures and examines the total set of "possible relationships in a multidimensional, usually non-quantifiable, problem space. It helps to reduce the chance that events will play out in a way that the analyst has not previously imagined and considered. MA allows for all ideas to be considered as a first stage in the analysis process and as such is an exploratory method *par excellence.* Although the method is generic it works across three verticals the first addressing Uncertainty and Complexity namely: Ideation (Creativity & Innovation) and Technological Forecasting, Futures and Scenario Planning, and Systems Uncertainties (aka "wicked problems"). The second vertical specifically engages with Industrial and Organisation Sectors such as: Defence and Security, Life Sciences, Pharmaceuticals and Health and Engineering and Design Engineering. The third vertical addresses issues such as CSR, Governance, Diversity, Social Exclusion and Policy topics.

1. INTRODUCTION

This paper presents an overview of the method – in terms of its history, current stage of development, on-going R&D into its functionality and future potential. The paper begins (2) with a brief description of what is MA and it's current state-of-the-art (SoA). The bulk of the paper is given over to its current methodological process and analysis of further development potential. This includes where and how it has been used(3), followed by a review of the awareness of the method(4) in the market and importantly amongst OR practitioners. This section prepares the ground for a discussion as to the perceived Pros and Cons of the method (5). Section (6) introduces how recent research helped to produce an updated software assisted version of MA, in effect the current "state-of-the-art". There follows a detailed presentation of future enhancements (7), that have been specifically identified and have been incorporated into short term development objectives as well as a statement of more medium term R&D objectives. Section 8 introduces a discussion as to longer term potential areas of development involving integration of data analytics and artificial intelligence technologies.

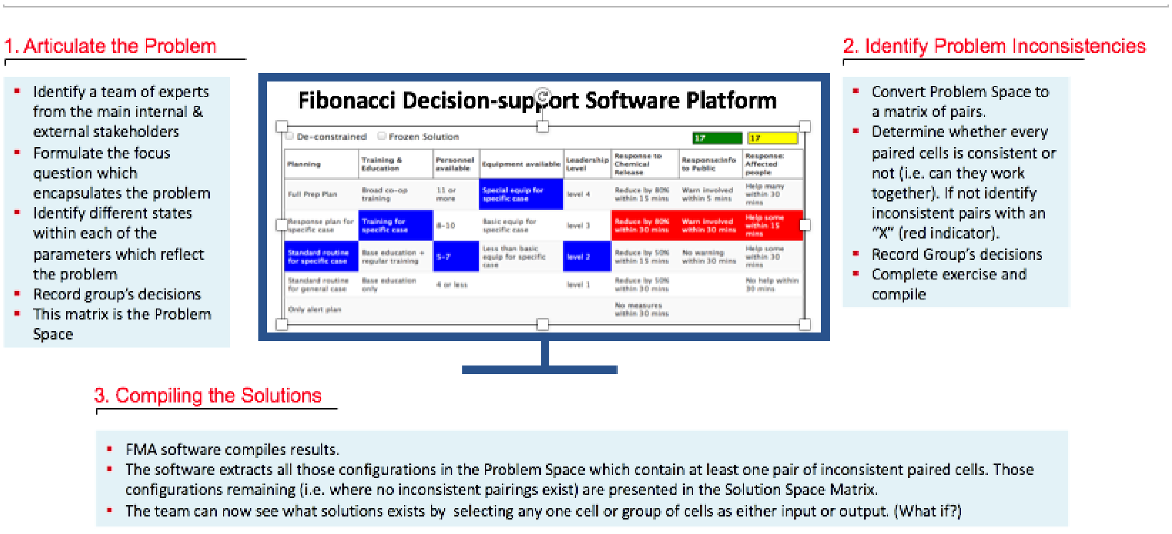
2. WHAT IS MA & HOW DOES IT WORK?

MA helps structure problems and support complex decision making, that have high levels of uncertainty. It can also be referred to as "Totality research", "Idea factory", "Strategic Options Analysis" or to use Red Team terminology "Alternative Analysis". Such problems are not only complex but exacerbated by high levels of interconnectivity adding further complexity to the problem. By identifying all the variables relating to the problem, all possible combinations of these variables (configurations) are examined. Each set of configurations generated can be considered as a bundle of attributes. Through a reductive process, whereby inconsistent individual pairs of variable are filtered out with the help of software, computing only those configurations where all variables are consistent with one another, a final set of viable solutions can be compiled for further analysis. The salient features identify that:

- MA is a method that systematically structures and examines the total set of "all possible relationships" in a multi-dimensional, usually non-quantifiable, problem space.
- It allows for all ideas to be considered as a first stage in the analysis process. It is an exploratory method allowing us to identify all potential viable outcomes.
- MA provides management and policy makers with the ability to identify informed and innovative options when confronted with complex problems, particularly under conditions of uncertainty and compounded by high levels of interconnectivity.
- The process mitigates the risk of making the wrong decision in the face of uncertainty. It does this by structuring the problem, filtering out inconsistent relationships within the problem boundary, to generate a much reduced set of workable solutions. As an idea factory, it processes unstructured ideas and concepts and renders them down to a set of modular components, which can be used to help in the construction of new and innovative "products" or concepts.
- The process, on the one hand helps reduce the chance that events will play out in a way not previously considered (mitigating negative unintended consequences), yet on the other, can identify innovative options also not previously considered (positive unintended consequences).
- This reduced set of viable options accommodates multiple perspectives to deal with uncertainties and new phenomena, rather than prescribe a single solution.

How does it work?

The MA process consists of three core phases: Problem articulation, identification of the inconsistencies with the problem space, and finally, compilation of the solutions.



The latest software interface for the three main parts of the process is shown in section 6.

3. WHERE CAN IT BE USED?

The method works across multiple areas, sectors and topics. It can be applied as 3 main verticals:

3.1 Applications to address Uncertainty and Complexity divide in turn into three core areas

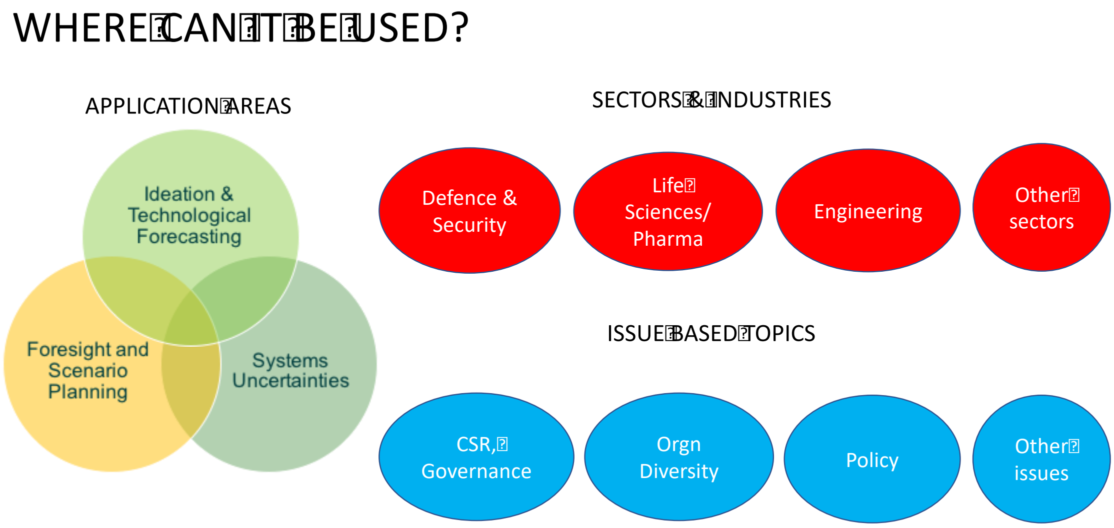
- Ideation (Creativity & Innovation) and Technological Forecasting
- Futures and Scenario Planning
- Systems Uncertainties (aka "wicked problems")

3.2 Industrial and Organisational sectors (non-exclusive) such as

- Defence and Security
- Life Sciences, Pharmaceuticals and Health
- Engineering and Design

3.3 Issue based topics (non-exclusive) such as:

- CSR
- Governance
- Organisational diversity
- Social exclusion
- Policy development



Different combinations of the three core application areas and how it they are used across different sectors and issue segments include:

- *Ideation (Creativity & Innovation) & Technological Forecasting* – New types of combustion and jet engines, electrical torque devices, concept design for a new vacuum cleaner, etc.
- *Foresight & Scenario Planning* – Alternative, contingent, regional and national futures e.g. quality and nature of political integration, identifying weak signals relating to various technologies, criteria for military engagement in large urban conurbations in 2035.
- *Wicked Problems (Systems Uncertainties)* – Developing policy to combat social exclusion, integrating organisations post merger or acquisition, how to embed diversity practices within organisations, immigration and integration, organisation transformation.
- *Ideation and Foresight* – How to develop a modular product that can be updated to reflect changing technological capabilities over the next 10 years, bio-mimicry and its future impact.
- *Ideation and Wicked Problems* – How will humans adapt to and control technological advancement in artificial intelligence? How will innovations in social media impact human behaviour and social responses?
- *Foresight and Wicked Problems* – What are future options for the role of the state? What are the dangers of an over concentration of power in the hands of media conglomerates?
- *Ideation, Foresight and Wicked Problems* – What might be the unintended consequences on privacy of the "internet of things"

4. AWARENESS

Over 70 years the number of dedicated books and papers has been somewhat sparse. There have only been 4 dedicated books plus 7 Book chapters. What is of greater concern is that for an “applied” method very few studies (including papers) actually present the outcomes using MA and how they are of value to the user. This paucity of material on the topic has not assisted in bringing MA into the mainstream of problem structuring and decision support methods.

A literature survey carried out by the author, using as source material 19 “aggregators” identified 835 different Methods, Tools and Techniques (MTTs) in the broad domain of Decision Support Mthods (DSMs). The aggregator references (or sources) are as follows: Rosenhead & Mingers 2001, ,Van Leewen & Terhurne 2010, University of Cambridge Institute of Manufacturing website 2014, Sands 1979, Creating Minds.org 2014, Multi-criteria decision making (MCDA) –Wikipedia 2014, EU Commission 2009, Krogerus & Tschappeler 2011, Van Assen, van den Berg & Pietersma 2009, Miscellaneous 2013-2014, Create Project 2005, Rigby 2011, Baxter 1995, Evans 2013, O’Brien 2009, Heuer & Pherson 2011, Porter 2004, Cross 2008, Slupinski 2013.

The selection covered a range of MTTs including the following domains, Decision Support and Decision Making, Creativity and Innovation, Design and Product Design, Strategic, Operational Management & Operational Research. Across all these domains a number of keywords relating to these sub-disciplines were used including:

Decision support, decision making, creativity, innovation, design, decision methods, technological forecasting, scenario planning, futures, problem structuring, strategy, strategic models, management models amongst others.

It is to be noted that whilst this list can be considered as comprehensive, it is not a definitive one, and the author acknowledges there may be omissions. It was interesting however, that these 835 items were represented across 1079 identified sources. What is surprising here, is that the statistic reveals only 23% of individual items appear more than once!

The frequency profile across the identified sources reveals the following:

- 710 items only had one source reference (representing 85% of the total items covered by the sources i.e. 710/835). This in itself is a significant sign of extreme diversity (if not profligacy), of terminological usage.
- Of the 19 aggregator inputs the maximum coverage is only 11 out of 19 or 58%. The 4 items appearing 9 times or more, (i.e. appearing in 47% of the aggregator lists) are as follows: DELPHI 9, Brainstorming 10, MA 11, SWOT 11

The surveys included in the aggregator list are: O’Brien (2009) with 40 items, Porter (2004) with 51 item, FORMAT (2013) with 91 items. Only O’Brien’s study is based on a survey of practitioner responses, the other two being studies compiled from extensive literature reviews and other surveys; in effect using secondary rather than primary sources.

O’Brien’s survey (135 practitioner respondents), specifically addresses that area of OR/MS (Operational Research/Management Science), which supports strategic development of an organisation, identifying some 8 key elements for such development.

The O'Brien study identifies a number of "hard" (i.e. quantitative) and "soft" (qualitative) methods. Importantly it confirms that the "soft" approaches, many of which are within the PSM (Problem Structuring Method) domain, are still not widely known. O'Brien (2009) goes on to state that SWOT appears to be one of the most popular methods not only in her survey but in others as well (Stennfors et al. 2007), (Tapinos 2005). What she did find surprising was the lack of awareness by respondents of some of the classic strategy tools, including Porter's five forces (with a 45% not identified rate), PESTLE (26% unaware). However,

"the picture for soft OR/MS tools in the 'never heard of' category is perhaps the most bleak. Heading the list (of 12) tools) were morphological analysis of which 71.11% of respondents reported that they themselves had never heard …." (O'Brien F. 2009 p.16).

O'Brien confirms that there is a large collection of tools that are considered never or rarely used to support strategy (amongst which is MA).

Porter's research, unlike O'Brien's, is in effect a study of various technological forecasting analysis methods rather than a user survey. Similarly the FORMAT Consortium study (Forecast and Roadmapping for Manufacturing Technologies) by Mateusz Slupinski (2013) uses secondary sources rather than primary responses from practitioners (as per O'Brien). Slupinski's study is based on a family of 91 methods and tools and restricts itself to just the Technology Forecasting area. Nonetheless all three studies highlight the feature that, although MA is identified, its uptake is small when compared to other methods in the same family.

5. PROS & CONS

The author considers that the advantages highlighted are strong enough to make the method worthy of consideration by decision analysts and policy makers. Nevertheless, these advantages in themselves have not created a critical mass of evangelists that would allow MA to become a leading decision support method. It is not surprising therefore that a number of disadvantages have been identified within both the literature and user responses. Research not only identified a number of known disadvantages but crucially through action research and case study feed-back, identified additional constraints, largely of a process nature. Subsequent development of the prototype and iterations has attempted to address many of these concerns. These have been overcome in the latest version of the software and, importantly, the supporting processes.

The advantages and benefits of MA can be summarised as follows.

MA has several advantages over less structured approaches and to re-iterate the observations made in section 2, it:

- Helps to discover new relationships or configurations, which may not be so evident, or which, might have been overlooked by other – less structured – methods particularly in a multi-dimensional problem space - identifying un-intended consequences (good & bad) as well as feasible alternatives

- Encourages the identification and investigation of boundary conditions, i.e. the limits and extremes of different contexts and factors (Totality Research).
- Has definite advantages (visual) for communication and –especially – for group work.
- Facilitates the identification of finding possible solutions to complex problems characterised by numerous parameters.
- Has a richness of data – it can provide a multitude of configurations not yet explored.
- Provides systematic analysis – the technique allows for the analysis of viable options under conditions of uncertainty, complexity and connectivity.

The disadvantages fall into three categories:
Epistemological, Process, and Software.

- Epistemological
    - Too structured
    - Prone to being too subjective
    - Overly generic
    - Narrow lens – not the right method
    - Issues emanating from the combinatorial explosion
    - No consistent terminology
- Process
    - Rigidity and over prescription of method process such maximum number of parameters, expert team size, process format (in terms of time and workshop approach), exhortation to have two neutral facilitators.
    - Need for two dimensional flexibility, sequence process and number of participants
- Software
    - Accessibility
    - Limited software development to date
    - Platform constraints
    - Licencing issues
    - Feature limitations
    - Integration with other methods

In spite of the apparent methodological advantages, the disadvantages have acted as empirical barriers to the achievement of attracting a wider audience – or in marketing parlance – a low conversion rate.

A number of these concerns were recognised by the author prior to a formal academic research programme. It was, however, not until prototype software became available, that the full implications of the constraints, largely of an empirical nature, became apparent. Live testing, and case study feedback incorporated into an Action Research programme allowed for both acknowledged issues (pre) to be refined by empirical research (post) and incorporated via iterative research into a refined empirically adjusted MA model.

6. IMPACT OF RECENT RESEARCH

The principal rationale for the research was to address the "Cons". These concerns were seen to act as a barrier to access by practitioners wishing to apply MA, as well as broadening its appeal as a viable decision support method. To allow for basic testing and identification of user response a prototype on-line MA model was developed in 2014.

Having been stress tested via both experimental projects and live case studies, the combined processes and software was developed so as to be robust enough for commercial deployment. Research allowed for the post prototype model to achieve the objectives set for performance and make a major contribution towards achieving the prime purpose of the research.

However, in parallel to the development and implementation of a viable working prototype, additional enhancements to the basic model were identified. Since completion of the academic research phase a number of improvements have been identified and in a number of cases been implemented.

Enhancements completed

Stand-alone version.

A separate stand-alone version of the MA model was released in June 2015 and subsequently updated in June 2017. The stand-alone variant was developed for three major reasons.

1. Speed of compilation for large configuration problem spaces.

Live testing of the on-line version found that the compilation time of the CCA into a solution space and the separate selection of individual configurations (or scenes) within the solution space component, could be slow if both the configuration size of the problem space and/or the number of compiled solution scenes were large. Large could mean over 50k configurations and where the number of constraints in the cross consistency matrix were low enough to generate a solution space with a still large number of configurations (e.g. a reduction of only 70% of the problem space). Although testing showed the core reduction algorithm to be robust, the compilation and response time was subject to the quality of the server and its connection. In essence, bandwidth constraints when on-line could cause a slowing down of this part of the process. The development of a separate off-line stand-alone version overcame the restrictions caused by on-line access. Testing indicated that compilation of examples with up to one million configurations were compiled in less than 5 seconds. A 3.5 million problem space configuration took only 20 seconds to compile with minimal waiting time when selecting individual scenes or configurations in the solution space (under 2 seconds).

2. Security considerations

A major defence sector client considered that accessing the software via the internet (on-line version) was a major barrier to its high level security protocols. The client thus requested a stand-alone version of the product in addition to the more powerful compilation capabilities that such a version would allow. This was duly delivered in a CD-ROM format so the version could be loaded directly into the client's stand-alone lap-top.

3. Licencing

In addition to security considerations, discussions with major corporates have indicated a preference for licencing the software and supporting processes – subject to the user demonstrating that it is able to carry out skilled facilitation in conjunction with use of the software. A formal training programme in the operational use of the model is being developed as part of the Licencing option. Hereto commercial access to MA software has been exteremely difficult to source.

4. Adding a third constraint - Normative

Ritchey (2011) states there are three types of inconsistencies or constraints to be considered during the CCA process. These are the purely logical contradictions (and identified by an "X" in the pair-wise cell); empirical constraints i.e. relationships judged be highly improbable or implausible on empirical grounds such as "we cannot deploy due to time taken to train operatives " (identified by a "P" , for Possible, in the pair-wise cell). Currently the software does not address the impact, at the CCA phase, of identifying a normative constraint (where a relationship is ruled out due to ethical or political considerations) – such as the use of thermo-baric weapons to eradicate well-dug in guerillas in difficult and complex urban areas;- the weapon whilst useful in saving our own casualties from street fighting is likely to incur high non-combatant casualties remaining in the area which in turn could alienate non-combatants from our cause.

Earlier Jantsch (1967) in his OECD report (1967), when discussing technological forecasting methods, identified two principal types; exploratory and normative. When evaluating various T-F techniques he places MA firmly in the "exploratory" group as it is "opportunity-oriented", whereas the normative approach is "mission-oriented" – with the danger that the latter can fall into the trap of becoming a self-fulfilling prophecy. Jantsch nonetheless, does indicate that the two forms can work together via iteration or in a feedback loop (in effect top-down and bottom-up planning). He makes the proviso that normative forecasting is only meaningful if two conditions are present:

1. If the level to which it is applied is characterised by constraints; normative forecasting can be applied to the impact levels (goals, objectives, missions) only if these conditions are sufficiently 'closed' by natural or artificial forces or by consensus; fully-integrated normative forecasting is applicable only to a 'closed' society.

2. If more opportunities exist and are recognised on these levels than can be exploited under the given constraints; normative forecasting is essentially an attempt to optimise, **which implies selection**. (author's bold type) (Jantsch E. 1967 p.34).

Ritchey (2011), re-enforcing this concern, warns that: "it is important not to allow normative judgments to initially influence the cross-consistency assessment". For this reason, he advises that only logical and empirical judgements should be allowed initially.

"Although normative judgements can, and often must, be made, they must never be confused with logical and empirical considerations. We must first discover what we judge as possible, before we make judgements about what is desirable" (Ritchey T. 2011 p.16).

This is another way of agreeing with Jantsch, about not allowing normative viewpoints to select conditions in advance – or at least not too early in the exploratory approach so as to contaminate outcomes and reduce the impact of discovering uncomfortable truths.

Thus care is required when applying normative constraints as it could interfere with the identification of unintended consequences and pre-judge “thinking about the unthinkable” – a key outcome of using MA. For example, whilst it may not be acceptable for “our organisation” to behave in a particular manner, a different organisation may be less constrained due to a different moral perspective that is totally alien to us and thus be seen as a real possible solution or outcome.

Given these concerns, it is apparent that in certain scenarios normative considerations may be justified as an additional step. It is interesting that our partners at NATO have picked up on this and are keen to develop the inclusion of a “Normative” constraint filter – subject to the user being made aware of potential limitations in the use of such constraints. Incidentally, the stand-alone version with its ability to duplicate problem spaces relating to the same project can employ a form of Gap Analysis by comparing solution spaces with and without the normative constraint. In the model’s process guidelines, however, the user is warned that engaging the normative constraint option should only be carried out once the logical and empirical constraints have been identified and solutions generated.

Multiple versions of a project

Empirical research based on user feedback has indicated that a useful feature is the need to create multiple versions of the same project. The MA method is best served when the user is able to iterate a project – whether this be variants of the problem space itself or indeed variants of CCA within a single project. Such flexibility enhances the number and validation of options that the user may wish to consider as part of the overall decision support process. This option is important at the problem structuring stage where in the absence of a facilitator, different emphasis may be incorporated by different stakeholders within the space defined by the initial focus question.

The latest upgrade allows the user to set-up different versions of the same project at both problem space and CCA phases of the exercise.

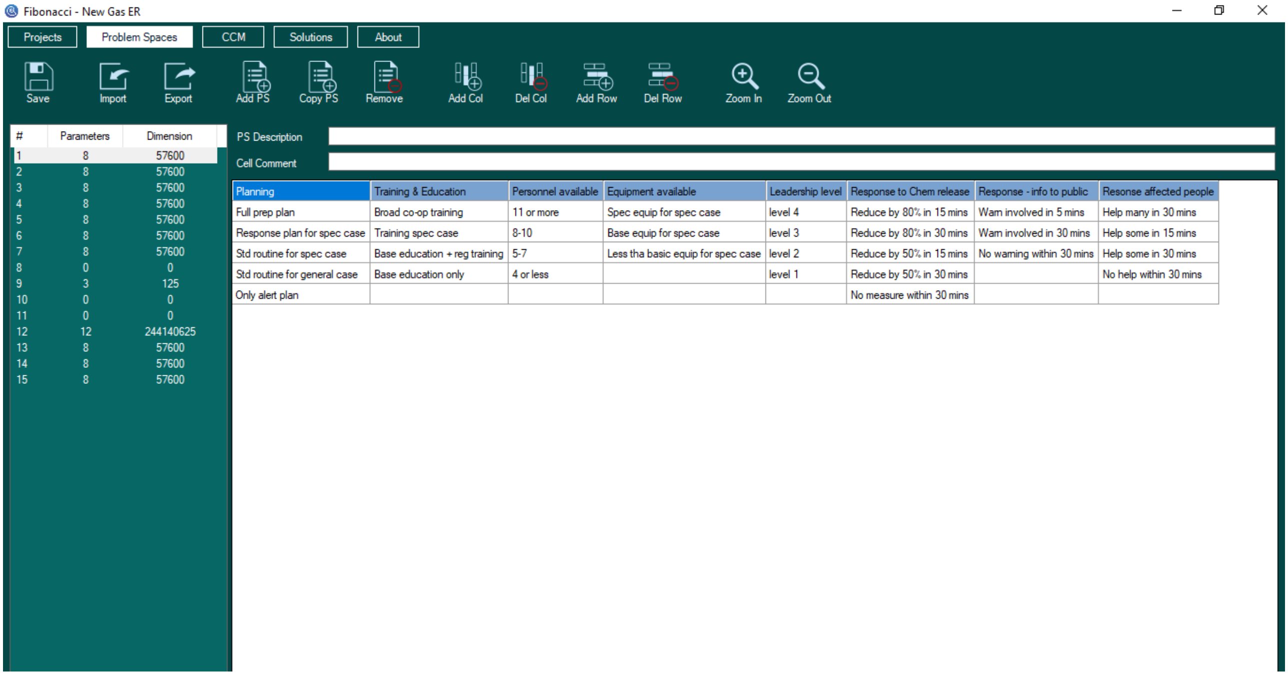
Comparisons between versions can be easily made by flicking to and fro between the listed versions. Hard-copy/off-line analysis of the problem space and CCM pages can also be carried out via the “Export” function into Excel.

This feature thus allows for the team leader, to have access to individual off-site workshop team members with a copy of the CCM. These team members can then complete their own CCMs, return the completed schedule and the team leader can set up separate variants of the project reflecting the diverse inputs from team members. The team leader can then analyse these results and identify the key variances, engage with individual team members as a facilitator in order to arrive close to a consensus. The inclusion, at this stage, of this feature acts as a half-way house for a planned enhanced feature whereby off-site collaboration by team members and CCA analysis can be fully automated.

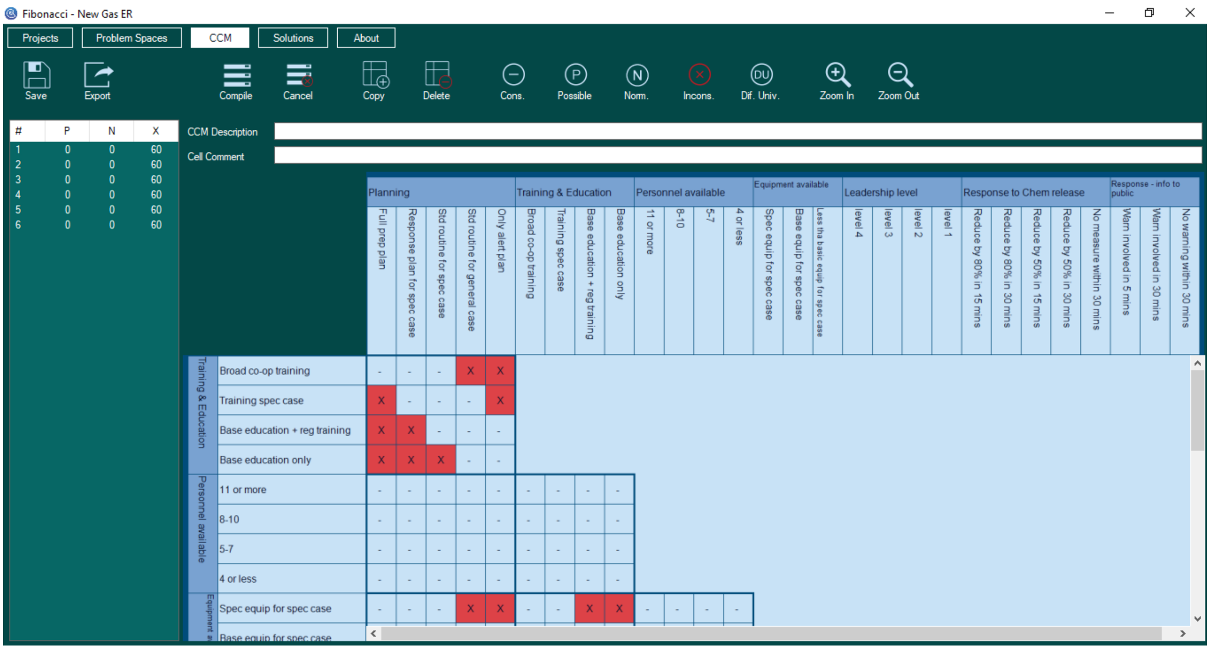
A new feature has been introduced within the solution space which allows the user to select multiple input states under a single parameter. This allows the user to compare cumulative options as additional states are used to constrain scenarios – in effect, providing an “AND” option in addition to the “OR” option in earlier versions of the model.

The latest software interface across the three main components, Problem Space, Cross Consistency Assessment and Solution Space, are shown below.

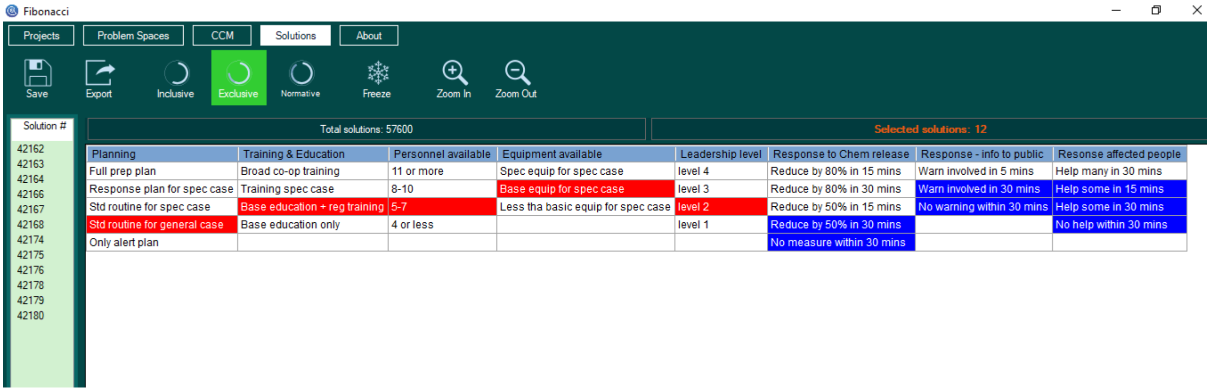
1. The Problem Space



2. Cross Consistency Assessment Matrix (pair-wise analysis) based on the transformation of the problem space.



3. The Solution Space (post-compilation of the CCA results).



In addition, each of the parameters and states in the problem space, as well as the individual pair-wise cells in the CCA matrix can be provided with a text box. This feature acts as an audit trail to record the rationale and description for each component selected to populate the problem space matrix and for the choice of constraint in each cell in the CCA matrix. These notes can now be exported back into Excel to be published in consolidate audit note form.

7. FUTURE ENHANCEMENTS IDENTIFIED

Current short list

Two options for **reducing large solution space configurations** even further have been researched and deemed to be feasible – the introduction of **Morphological Distance (MD)** and **Linked Parameter Reconciliation (LPR)**.

- - Morphological Distance (identification of real innovation amongst solutions)
- - Linked Parameter Reconciliation (LPR) to handle large configuration problem spaces (500k +)

In addition the need to engage with a broader range of stakeholder/experts (not just a maximum of 7) and who may be geographically dispersed has initiated the inclusion of Collaborative and Remote input processes.

Future areas of engagement

- Integration with other methods across the Uncertainty/Risk spectrum have been identified.
- Introduction of hierarchy and weighting factors into the process
- User feature enhancements

Current short list

Morphological Distance

The ability to reduce the large number of configurations generated by the MA Problem space matrix has been addressed with varying degrees of success by deploying reductive software in conjunction with pair-wise analysis (CCA), (including Actified, Morphol, Casper/Carma & Memic and even FMA). However even when using software to majorly reduce the number of internally consistent configurations, the remaining configurations within the solution space can still be voluminous. Where large problem spaces do occur, even current levels of reduction of 95% plus can still leave solution spaces of sizeable proportions. For example with a problem space of some 1,500,000 configurations, a 95% reduction level post CCA, still leaves a solution space of 75,000.

One way to reduce the set still further is to run a second iterative exercise and "nest" some of the original parameters and states within the problem space matrix. However, iterative nesting can inhibit the efficacy of the method since certain processes, particularly in the product design area, cannot afford to subsume, via nesting, important system and sub-system components. In other words, the parameters and states present in, for example, design and product analysis, do not readily lend themselves to being constrained with parameters restricted for reasons of computational expediency.

The Morphological Distance option can work independently as a configuration reduction filter. Originally proposed in 1969 by Robert Ayres, in his chapter on Morphological Analysis in "Technological Forecasting and Long-Range Planning" (McGraw-Hill Inc. 1969), he introduced the concept of "morphological distance". Ayres defines morphological distance (MD) as being the distance between two points in the (problem) space and is:

"the number of parameters wherein the two configurations differ from one another. Two configurations differing in only a single parameter are morphologically close together, while two configurations differing in many parameters are morphologically far apart." (Ayres R. 1969 p.81).

Note: It is important to clarify here that Ayres' use of the term parameter is really a discrete state within the selected parameter, and that a configuration consists of a selected individual state in each of the parameters which make up the overall problem space.

Ayres suggests that configurations within a morphological space can be divided into three main sectors; in effect a triage division. It should be noted that the areas and boundaries of each sector will be subjective according to the particular technology or design being evaluated, and to the consensual subjectivity of a team of experts introduced to assist in determining the problem parameters and states of the morphological space. This same team should be expected to identify and agree through consensus, those individual configurations which, when brought together as a cluster, make up what is deemed to be "existing art" or State-of-the Art (SoA).

The three sectors Ayres specifies are:

1. Known or Occupied territory (OT) – composed of those configurations identified as representing "existing art" or State of the Art (SoA). This is the area where minimal innovation is likely to occur because it is already known about.
2. The Perimeter Zone (PZ) – those configurations which contain between 2 and 3* * parameter/states different from SoA. Configurations with just a two parameter/state distance, are closest to the SoA or Occupied Territory sector and thus will have limited innovative potential. In essence they can be said to represent some form of basic product development: the low risk option. On the other hand those configurations with a parameter/state distance of 3, show a heightened level of innovation being further away from OT at the outer fringes of the perimeter zone.

3. "Terra Incognita" or Unknown Territory (TI), is composed of those configurations characterised by a distance factor of, say, 4* * or more parameter/states from SoA. According to Ayres these configurations are so different from SoA that **they are likely to embrace configurations containing something which has not previously been considered, thus increasing the probability of some form of technological breakthrough.** Possible configurations appearing in this sector are as likely to be truly creative as well as innovative. In addition, they may reflect unintended consequences – good or bad, but nonetheless possible and worth identification and examination. Conversely where refinements/improvements occur which are similar to an "existing art" configuration (differing up to 1 parameter/state cell), there is little chance of a breakthrough.

* * It is important to note that the criteria determining the degrees of distance within each of the boundary sectors boundaries are flexible, depending upon, amongst other considerations, the overall size of the problem space (number of configurations) and crucially the number of parameters.

Specifically, Ayres mentions that:

"The probability of a breakthrough in a technological area, per unit of time, is a decreasing function of its morphological distance from existing art, other things being equal" (Ayres R. 1969 p.81).

In other words, new developments will tend to occur nearer to older, established ones, mainly by gradually transforming through growth or external addition (accretion), from the borders of state-of-the-art clusters into adjacent undeveloped areas. One could also use the analogy of osmosis to illustrate this slow transfer.

The user of the method now has the choice to review different risk criteria, as represented by the increasing morphological distance inherent in each of the 3 distance categories.

Two additional activities are required to refine the solution using this method.

1. The same expert team used to create the problem space and work through to the solution space, should be used to identify those configurations which are closest to current state-of-the-art. This part of the process is helped by the team exploring the solution matrix and those configurations that approximate to OT (SoA) – via the visual scene list within the software.
2. The solution space scene list is reduced by the MA software from the original problem space configuration database. Each state within each parameter will have been identified by a "cell position" code. Each set of configurations will have a unique set of state cells within that configuration. For example, in a 6 parameter problem space with each parameter having variable states, a particular multi-parameter configuration could have a profile consisting of the following: A1:B3:C1:D2:E5:F6.

In activity 1 above, the team will have identified those clustered configurations, which conform to the team's OT criteria. These individual configurations within the cluster are identified within the solution space database. The algorithm subtracts these configurations from the solution database and identifies the remaining, solution space configurations, also determining the distance of each surviving configuration from an initial problem space.

We can now apply MD Triage to those configurations or scenes which have been deemed to be viable or internally consistent following pair-wise (CCA) analysis and not to the overall set of configurations in the problem space field.

When Ayres originally developed the concept of morphological distance to morphological analysis, there was no effective way of efficiently reducing the, very often, large problem space to a manageable solution space. He used MD as a first phase field reduction exercise.

Rather than use the Ayres distancing method to analyse the original problem space, it is now proposed that MD is introduced as a solution space qualifier post cross consistency and post compilation of the solution space.

Currently this approach has only being tested in relation to what can be termed the "Product & Technology Ideation" stream. This stream has its roots in the original Zwicky, and latterly Ayres, interpretation, whereby MA is used (using Zwicky's explanation) "to identify, index, count and parameterize the collection of all possible devices to achieve a specified functional capability". In essence MA is being used to seek out new technology product design configurations.

A recent case study to concept test this innovation (unpublished) by Garvey, Varnavides and Childs (2015) entitled *"Parametric Modelling using a visual algorithmic editor for analysing morphological analysis configurations"* gives a fully worked example of how MD works. The subject of the study was on Apartment Typology. Of great interest to designers is that large problem spaces containing multi-variable inputs by the designer can be majorly reduced using both MA followed by MD triage to help identify viable design options significantly removed from standard state-of the-art designs. The results showed that a 99.9% reduction of an initial problem consisting of 155,520 configurations (based on a 10-parameter space) could be reduced to a mere 213 internally consistent options. These final 213 solutions post Morphological Distance were found to be distanced 4-5 parameters away from existing, state-of-the-art, solutions. These "Terra Incognita" solutions, were deemed to help identify viable design options significantly removed from standard state-of the-art designs and can be considered to offer innovative, non-standard insights for designers seeking alternative outcomes. The outputs were then processed by a visual algorithmic editor and output as tri-dimensional CAD models.

Linked Parameter Reconciliation (LPR) to handle very large problem space configurations
As already highlighted one of the traditional arguments against the use of morphological analysis has been that the resulting total number of configurations, can be so large as to be unmanageable for all practical intents and purposes. Empirical case studies and user feedback indicate it is less demanding, both in terms of time and emotional energy and effort, to carry out two smaller CCA exercises than one very large one. Moreover, it is also most probable that the resulting solution space post CCA will still be large and a challenge to analyse. One option is to split the problem space into 2 smaller matrices with the proviso that the 2 matrices have one parameter (and parameter states) in common, allowing them to be linked. In effect this parameter acts as an interface or link.

The following acts by way of a prototype design brief for the development of a new feature allowing for the easier handling of very large problem spaces.

Outline of process

By way of example, in an 8 parameter problem, it can be seen that by allocating an increasing number of parameter states (or dimensions) to each parameter, the number of configurations in the problem space dramatically increases. In other words the size of the problem space is a product of both the number of parameters and the number of states within each parameter. In the schedule below different numbers of states are allocated to each of 8 parameters. The total number of configurations, being a product of the number of parameters and states within them, range from 256 in a two state profile to nearly 2 million in a 6 state profile!

	P1	P2	P3	P4	P5	P6	P7	P8
2 states/ parameter	2	4	8	16	32	64	128	***256***
3 states/ parameter	3	9	27	81	243	729	2187	***6561***
5 states/ parameter	5	25	125	625	3125	15625	78125	***390625***
6 states/ parameter	6	36	216	1296	7776	54432	326596	**1959552**

Example of Combinatorial Explosion based on increasing parameters and states.

However even post CCA/pair-wise analysis, the remaining solution space can still contain a large number of internally consistent "solutions". For example a moderately large problem space consisting of, say 150,000 configurations could be reduced to 7500 possible configurations at a 95% reduction, whilst in the above schedule the 6 state version would yield 98k solutions at 95% reduction (5% of 1.96m).

It was mentioned earlier that "nesting" might be a solution to reduce the parameter field. In certain application domains such as Design, iterative nesting may inhibit the efficacy of the method since the (product) design process cannot afford to subsume, via nesting, important system and sub-system components.

To test the efficacy of the principles behind the LPR process but using a smaller problem space, an example based on 8 parameters, was set up as follows. An 8 parameter problem space was split into two smaller matrices with the AP4/BP1 *parameter vector set being used as the link.*

PSMA

AP1	AP2	AP3	**AP4**
AP1S1	AP2S1	AP3S1	**AP4S1**
AP1S2	AP2S2	AP3S2	**AP4S2**
AP1S3	AP2S3	AP3S3	**AP4S3**
	AP2S4		

PSMB

BP1	BP2	BP3	BP4	BP5
BP1S1	BP2S1	BP3S1	BP4S1	BP5S1
BP1S2	BP2S2	BP3S2	BP4S2	BP5S2
BP1S3	BP2S3	BP3S3		BP5S3
	BP2S4			

108 216 7776

36 72

The treatment of the identical link parameters AP4 and BP1 and their internal states can be expressed as follows:

AP4S1= BP1S1
AP4S2 = BP1S2
AP4S3 = BP1S3

The relationship between these three sets of identical cells will be seen to be of great importance to the process as explained below.

Post CCA pair-wise analysis, the Solution Spaces produce the following scene lists (configuration strings) respectively for the two matrices PSMA and PSMB.

Scene List	PSMA			
7				
Scene 1	AP1S1	AP2S1	AP3S1	**AP4S1**
Scene 2	AP1S1	AP2S1	AP3S1	**AP4S2**
Scene 3	AP1S2	AP2S2	AP3S2	**AP4S2**
Scene 4	AP1S2	AP2S3	AP3S2	**AP4S2**
Scene 5	AP1S2	AP2S3	AP3S2	**AP4S3**
Scene 6	AP1S3	AP2S3	AP3S2	**AP4S3**
Scene 7	AP1S3	AP2S4	AP3S2	**AP4S3**

Matrix A

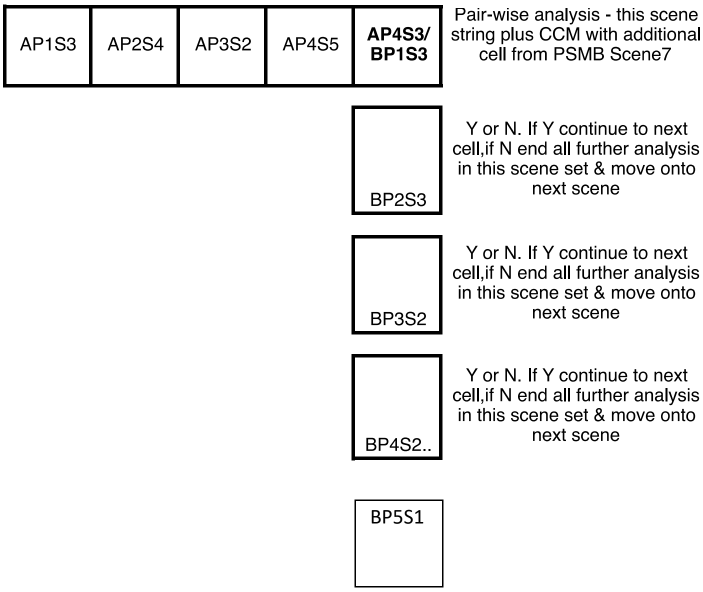
Scene List	PSMB				
11					
Scene 1	**BP1S1**	BP2S1	BP3S1	BP4S1	BP5S1
Scene 2	**BP1S1**	BP2S1	BP3S1	BP4S1	BP5S2
Scene 3	**BP1S1**	BP2S1	BP3S1	BP4S1	BP5S3
Scene 4	***BP1S1***	*BP2S2*	*BP3S2*	*BP4S1*	*BP5S1*
Scene 5	**BP1S2**	BP2S2	BP3S2	BP4S2	BP5S1
Scene 6	**BP1S2**	BP2S3	BP3S2	BP4S2	BP5S2
Scene 7	**BP1S2**	BP2S3	BP3S2	BP4S2	BP5S3
Scene 8	**BP1S3**	BP2S3	BP3S2	BP4S2	BP5S1
Scene 9	**BP1S3**	BP2S4	BP3S3	BP4S2	BP5S2
Scene 10	**BP1S3**	BP2S4	BP3S3	BP4S2	BP5S3
Scene 11	**BP1S3**	BP2S4	BP3S3	BP4S2	BP5S1

Matrix B

Based on the linked pairs identified above we can see that Scene 1 in PSMA and which ends in AP4S1 can be matched with Scenes 1, 2,3,and 4 in PSMB. All these four scenes in PSMB have a common link to Scene1 in PSMA, namely the twinning of AP4S1and BP1S1. Similarly the three scenes in A ending in AP4S2, of which there are 3, can be matched against PSMB Scenes 5, 6 and 7 beginning with BP1S2 as AP4S2=BP1S2, and so on. In total there are 29 linked scenes to be isolated and analysed (1x4, + 3x3, + 4x4).

Each of the consistent split scenes in PSMA and PSMB can now be evaluated. For example a CCA exercise for scene 7 in PSMA, with a configuration of AP1S3, AP2S4, AP3S2 and **AP4S3,** can be run against the latter's twin in Matrix B, BP1S3. There are 4 scenes in PSMA ending in S3 (as in AP4S3) to be matched with those 4 scenes beginning with BP1S3 in PSMB.

We now examine how whether each of the states in scene A7 is consistent or not with those states in scene B8, (this being the first of the scenes in PSMB to be twinned with AP4S3). The process begins by assessing each of the A7 states with the second state in Scene 8, BP2S3, then BP3S2, BP4S2 & BP5S1. The process can be sped up, since once a state in the string being assessed in the relevant PSMB scene, is deemed to be inconsistent then each subsequent state in the string also will be inconsistent. The process then moves on to match Scene A7 with scene B9 governed by BP1S3. In Table T.6.6 below, we illustrate this by comparing Matrix A scene 7 (AP1S3, AP2S4, AP3S2 and **AP4S3**) with Matrix B scene 8 (**BP1S3**, BP2S3, BP3S2, BP4S2 and BP5S1).



Linking Process

It can be assumed that using this shorter version of CCA not all linked scenes (in our example totalling 29) will prove to be consistent as some non-linked states will yield a number of pair-wise inconsistencies thus truncating the 29 initial linked scenes.

Aggregation of pair-wise cells contained with different CCM inputs.

This allows imports of multiple individual team member CCMs so as to compile automatically an Aggregation Of Pair-wise Cells. Many of the team members could be located off-site.

Once all the individual user CCMs are completed and sent back to the facilitator/team leader then all those cells where ALL the users have taken a common position (i.e. consensus as to its status) are identified.

Up to here, all analysis processes are automated – by which the master CCM has been compiled and updated without having to refer back to individual team members. However subsequent phases may require direct intervention/discussion by the team leader where those individual team members, whose CCM input is at variance with other team members, needs to be addressed. It is at this point that “consensus” guidelines need to be established. For example at the beginning of the project the team will have been asked to decide what level of consensus they would be happy with – a simple majority of 1, a 2/3rds or 80% majority. The software will then analyse the aggregated CCM responses according to the consensus" tipping points" selected.

- Identification of those cells where there is no majority consensus, or where the response divergence is below the selected consensus level is then made. A "Delphi" style approach could be adopted and an iterative process of feedback to individual team members carried out until the consensus tipping-point is arrived at.

Future areas of engagement

Other potential areas for future research have been identified and where the MA platform can work alongside and be integrated with other Decision Support Methods (DSMs). The philosophy behind this approach is to present DSMs less as a discrete set of methods and tools but more as a holistic system. This permits mixing and matching of different methods so that both positioning across the uncertainty/risk spectrum and in relation to problem path sequencing (for example when addressing the various technology readiness levels), can be carried out. The topics presented are meant to identify research at both product and process development levels for practitioner applications as well as more academic and theoretical approaches.

- Integration with other methods across the Uncertainty/Risk spectrum have been identified to include for example:
    - The Analytic Hierarchy Process (AHP) plus MCDAs in general
    - Bayesian Belief Networks (BBN)
    - The Analysis of Competing Hypotheses (ACH)
    - Causal Layered Analysis (CLA)
    - Scenario Planning
    - Red Teaming
    - Strategic Choice Approach (SCA)
    - Robustness Analysis (RA)
    - Interactive Reconfigurable Matrix of Alternatives (IRMA)
    - TRIZ (Theory of Inventive Problem Solving)
    - Functional Analysis

- Introduction of hierarchy and weighting factors into the process

- User feature enhancements
    - Sector/Issued based applications within and across streams
    - User education and training to provide process and software plus facilitation (to include off and on-line training, user manuals and method accreditation.
    - Visual inputs and outputs in relation to multi-dimensional image-based algorithmic software (a form of image based morphological analysis) to support early stage visualization of concept design. Tests have been carried at an elementary level by linking MA to Grasshopper ™ graphical software and Tableau ™.

8. INTEGRATING ANALYTICS & AI.

Whilst the current MA methodology is sound with supporting software that is now commercially available, the overall process itself, notably the determination and population of the problem space and the somewhat onerous process of the CCA, has been shown to act as an operational constraint to gaining broader user acceptance of the overall process. It is demanding of resources in terms of time, number of personnel required to make up the expert team of stakeholders as well as the logistical matter of bringing the team together in one place for workshop type engagement. In addition, to what extent does this expert team approach reflect real objective evidence-based input? This set of issues requires an innovative re-appraisal if such constraints are to be mitigated if not overcome and which can allow MA to fulfil its full potential to a broader DSM constituency. It has been identified that a way forward might be to integrate data analytic and AI methods into the process to address these constraints.

State of the art processes for PSMs such as MA and other methods such as AHP prescribe a small (5-7) group approach, composed of heterogeneous experts, in order to establish the nature of the problem seeking resolution and crucially the number of main variables or parameters which describe the problem space. A secondary key requirement is to use this same group profile to cross reference each of the sub-components generated by the problem space (CCA for MA and more or less preferences in the case of AHP).

We believe that DA & AI technologies can help access higher levels of knowledge and objectivity than that currently prescribed by MA/AHP type methodologists. We consider that PSMs such as MA and AHP can reach a broader band of potential users to embrace decision analysts wishing to use such methods as *Personal decision support support systems (PDSS), Negotiation support systems (NSS) and Intelligent decision support systems (IDSS)* with particular emphasis on facilitating technologies such as contextual semantics.

Preliminary work in this area has started by engaging with a team of PhD researchers at Imperial College London. Initial analysis will address the comparing of outputs from the current (classic) process (in terms of quality of output for a problem space matrix, time taken and manpower resources required) against a prototype data-driven creativity engine. The latter allows the user to explore knowledge and support the discovery of creativity using visualization technology, and driven by an advanced data mining algorithm. Within the trial platform, users are able to freely explore words and phrases based on their knowledge, with results being shown in the form of lists and a network. Benefiting from advanced network visualization technology, the user is able to interact with the results shown in network, discovering knowledge associations and domains. Research is on-going with this project with initial results expected in the latter half of 2017.

9. CONCLUSIONS

- MA provides an effective means for tackling issues where there are high levels uncertainty and complexity.

- It is well suited to operate at the ”fuzzy” front end of problems with long gestation periods, numerous inherent risks, (structural, regulatory, existential).
- It can operate to tackle complex areas such as Ideation, Futures and ”Wicked Problems, across business sectors and issue driven topics.
- Accessibility (to supporting software) and user friendliness key in on-going R&D
- Opportunities exist to integrate MA within a broader toolkit of decision support methods.
- Integration of analytics and AI methods can help broaden validation and hence support better decision making under uncertainty.

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