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MAY 2020

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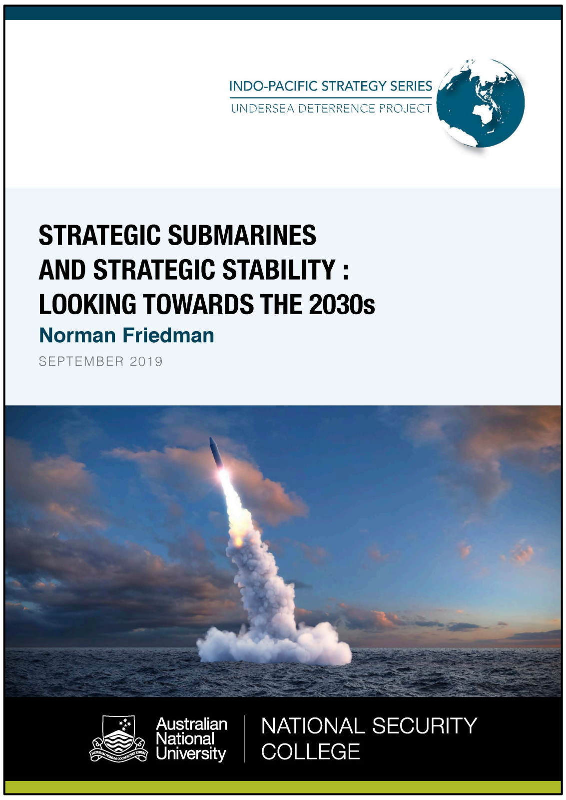

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Transparent Oceans?

The Coming SSBN Counter-Detection Task May Be Insuperable

A first principles analysis of new technologies and the detection of nuclear-powered ballistic missile submarines (SSBNs)[*].

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[*] This report is based on a workshop held on 21 and 22 May 2019. Workshop attendees included report authors in addition to Joseph Guillaume (Fenner School, Australian National University), Michael Shoebridge (Australian Strategic Policy Institute), Lachlan Blackhall (College of Engineering & Computer Science, Australian National University) and Greg Lane (Department of Nuclear Physics, Australian National University).

Foreword

The impact of future undersea detection technologies on the vulnerability of submarines – particularly those carrying nuclear weapons – will have profound ramifications for strategic stability in the Indo-Pacific region and globally. Strategic competition is accelerating in the Indo-Pacific, particularly in relation to China's assertiveness and power, and in spite of the great disruption of COVID-19. This rivalry involves increased investment in undersea nuclear forces. The race to detect and neutralise them will intensify.

Whether or not future detection technologies will render the world's oceans transparent, thus making SSBNs vulnerable to detection and destruction, is a matter of great and growing contention. That debate is at the heart of a major international research project led by the National Security College at The Australian National University, with funding support from the Carnegie Corporation of New York.

This publication, *Transparent Oceans? The Coming SSBN Counter-Detection Task May Be Insuperable*, is a significant output of that project.

In an earlier work in this publication series, *Strategic Submarines and Strategic Stability: Looking Towards the 2030s*, renowned naval scholar Norman Friedman concluded that the SSBN was 'likely to become less vulnerable in the future'. Certainly, knowledge of the oceans would continue to improve, but this would confer strategic advantage on the ability of submarines 'to operate in places where they will be difficult to find and track'. The second major report in this series, an edited volume assessing the Indo-Pacific SSBN debate, *The Future of the Undersea Deterrent: A Global Survey*, reflected varying conclusions among experts as to the survivability of submarines in a more 'translucent' ocean environment. This dialogue continues on The Strategist, the online commentary site for our partner the Australian Strategic Policy Institute.

This present report reaches a provocative conclusion that will sharpen the debate: that future technologies will make the oceans broadly transparent and that counter-detection technologies will not have the same salience in decades ahead as they have had previously. *Transparent Oceans?* represents a substantial and novel research endeavour, bringing together specialists from a wide range of scientific and defence capability backgrounds to take a structured and first-principles look at existing and prospective undersea detection technologies. Its use of a new subjective logic tool, *Intelfuze*, allows for realistic reasoning models and extended probabilistic logic. I commend Emeritus Professor Roger Bradbury for leading this innovative activity under the wider Undersea Deterrence project, and thank all of the contributors for their analysis.

Professor Rory Medcalf,
Head, National Security College
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May 2020

Summary

We considered the problem of disruptive changes in the technologies for detection of nuclear-powered ballistic missile submarines (SSBNs) and how they intersect with the growing or continued reliance on submarines for retaliatory nuclear capability. In simple terms, we sought to answer the question: Will future science and technology make the oceans transparent? We took a scientific perspective and considered the science and technology issues bearing on ocean sensing and the detection of submarines as anomalies in the water column. Our time horizon was the 2050s, as the next generation of nuclear-armed submarines become deployed through the 2030s and beyond. Our analysis identified broad areas of future science and technology – rather than specific 'hot' areas of the moment – that might have an impact on submarine detection as well as on counter-detection.

Our analysis used the estimative intelligence software tool, *Intelfuze*. It's used in the intelligence community to provide probabilistic assessments that are rigorous, transparent, defensible, and able to be updated. It is particularly suited for problems where the data are poor, uncertain and perhaps even speculative, and where there may be strongly divergent opinions on the quality and significance of those data.

Our assessments showed that the oceans are, in most circumstances, at least *likely* and, from some perspectives, *very likely* to become transparent by the 2050s. This suggests that, despite progress in counter-detection technologies, SSBNs will be able to be detected in the world's oceans because of the evolution of science and technology.

There were two strong implications from our results.

The first is that the favourable geographies that the West took advantage of in the Atlantic during the Cold War and more recently in the Pacific in its strategic rivalry with China will not have the same salience in the 2050s as during the Cold War. The evolution of science and technology is likely to make the oceans broadly transparent so that the strategic importance of geographic chokepoints in the ocean is likely to decline.

The second is that the evolution of counter-detection technologies will not have the same salience in the 2050s as it did in earlier times. Over the duration of the Cold War, Western submarines were able to reduce their detectability, at least acoustically, by some orders of magnitude. By the 2050s, our assessments show, progress in counter-detection will only reduce the probability of detection from *very likely* to *likely*. This is nothing like the reductions gained in earlier times, and insufficient to prevent the oceans becoming broadly transparent.

Even allowing for a generous assumption of progress in counter-detection in our analyses, we cannot see how counter-detection can possibly be as effective in the 2050s as it is today. We are forced to conclude that the coming counter-detection task may be insuperable.

Introduction

Our study addresses the problem of potentially disruptive changes in the technologies for detection of nuclear-powered ballistic missile submarines (SSBNs) and how they intersect with the growing or continued reliance on submarines for retaliatory nuclear capability. This study is part of a larger research project at the ANU National Security College on strategic stability in the Indo-Pacific region, with a focus on new technologies relating to undersea warfare and nuclear deterrence over a twenty year timeframe. This project is supported by Carnegie Corporation of New York.

In simple terms, we seek to answer the question: Will future science and technology make the oceans transparent?

We take a scientific perspective and consider the science and technology issues bearing on ocean sensing and the detection of submarines as anomalies in the water column. That is, we want to consider the physics, chemistry and biology of the ocean, how we may sense those properties in the water column, and how we may detect anomalies in those measurements. Submarines, from our perspective, are rare, large, massive, mobile, ferro-metallic objects in the upper few percent of a fluid column that is, relative to the subs, vast, homogeneous and static, electrically conducting, chemically and biologically active, and bathed in electromagnetic and gravitational fields.

Thus, from our scientific perspective, a transparent ocean means an ocean that may be sensed with sufficient granularity that large anomalous objects in the water column, like submarines, may be detected.

This is a hot area of scientific and technological research with many players. A recent news report[1] noted that Australia's CSIRO is partnering with the top Chinese marine science institute, the Qingdao National Laboratory for Marine Science and Technology, to better understand ocean physics. Qingdao leads China's national 'Transparent Ocean Initiative' with long-term projects to develop satellite-mounted light detection and ranging technology (LIDAR) to pinpoint submarines at depths of up to 500m.

Our time horizon is the 2050s, as the next generation of nuclear-armed submarines become deployed through the 2030s and beyond.

We know that the history of science shows that it isn't possible to project, in a detailed way, the future of science and technology more than a decade or so out from the present: there is just too much transformative surprise. Think of the unanticipated impacts of the discovery of lasers, the genetic code, PCR, CRISPR or graphene.

And we also know that the linear hypothesis – that science begets technology – is too simplistic. Science and technology are, and always have been, closely intertwined.

But we think it is still possible to block out some broad areas of science which, as they progress, will allow the development of new or improved sensing technologies. And it is also possible to block out some broad areas of technology which, as *they* progress, will use new science to create new or improved sensing technologies.

This growing suite of new science and technology needs to be organised, managed, integrated and deployed for it to be effective. Thus the capability for systems integration is itself an issue.

And, beyond the first-order homogeneity of the world's oceans, potential local differences in ocean geography may exist that allow the water column in some geographic locations to be sensed more easily than in other locations. Thus some states may be denied the opportunity to deploy sensors in some parts of the world ocean, and some states may have adverse local geographies that make sensing their submarines much easier. Thus the geography of the oceans, at various scales, is also an irreducible issue.

Finally, we need to consider the future of counter-detection technologies. We know that, from the Cold War onwards, counter-detection technologies allowed submarines to become increasingly stealthy, particularly in the

[1] Ben Packham, "Security Risk in China Marine Project," *The Australian* (Sydney), February 10, 2020.

West and particularly in the acoustic domain. We need to examine the potential for the exploitation of future science and technology to allow submarines to avoid detection in acoustic and, especially, in other sensing domains.

Our analysis seeks to identify the broad areas of future science and technology – the issues in play – that might bear on submarine detection as well as on counter-detection. We then seek to assess their combined impacts on the hypothesis that future science and technology will make the oceans transparent.

The assessment uses the estimative intelligence software tool, *Intelfuze*. This is a tool, developed for the intelligence community, to provide assessments that are rigorous, transparent, defensible, and able to be updated. It is particularly suited for problems where the data are poor, uncertain and perhaps even speculative, and where there may be strongly divergent opinions on the quality and significance of those data. It is eminently suitable for our problem domain.

The Assessment Process

Subjective Logic and *Intelfuze*

Subjective logic is a type of probabilistic logic that allows probability values to be expressed with degrees of uncertainty. It has been developed over the last 20 years by Audun Jøsang, a computer scientist and logician at the University of Oslo.[2] The idea of probabilistic logic is to combine the strengths of logic and probability calculus, meaning that it has binary logic's capacity to express structured argument models, and it has the power of probabilities to express degrees of truth of those arguments. In Jøsang's formulation, the central idea of subjective logic is to extend probabilistic logic by also expressing uncertainty about the probability values themselves, meaning that it is possible to reason with argument models in the presence of uncertain or incomplete evidence.

As a basis for intelligence assessment, subjective logic elegantly handles analytical conundrums that have confounded analysts for generations.[3] Intelligence analysis must deal with uncertain evidence and incomplete knowledge. Subjective logic can explicitly handle uncertainty, which enables analysts to create more realistic reasoning models that produce more informative conclusions than is otherwise possible with traditional Bayesian approaches. And importantly, subjective logic acknowledges that whenever the truth of a proposition is assessed, it is always done by an individual – it is, perforce, a subjective belief – and it can never be considered to represent a general and objective belief.

Belief-based reasoning with subjective logic provides a promising framework for modelling and analysing real world situations that are affected by uncertain and/or incomplete information, as well as with – and this is very important – conflicting opinions. Subjective logic provides a rich set of operators for combining belief opinions and can be used for modelling, classifying and analysing situations involving uncertainty such as Bayesian networks and trust networks.

In recent years, a new software tool, *Intelfuze*, has been developed and deployed in the intelligence community to take advantage of this new approach to analysis.[4]

The *Intelfuze* Workflow

The *Intelfuze* assessment process follows Jøsang's basic approach: first identifying the issues in play (the universe of discourse) including the key issue in question, then proposing arguments or models about the relationships between the issues (including conflicting ones), and then considering the evidence supporting the issues and models. The approach is well able to handle missing information – the absence of evidence – as well as conflicting information.

It's a highly structured and transparent process allowing alternative models and hypotheses to coexist within the one framework.

First Step – Identifying the Issues in Play

The first step is to identify the issues in play in the matter under consideration. This is usually done in an open workshop and is open-ended in the sense that, if new issues arise, they can be added to the analysis. These issues may be whittled down in workshop discussions to create an agreed and manageable set. In some tightly specified situations, the set of issues in play may be very specific. In the current situation, we are working on a very broad canvas, so the issues are also broad, high-level and conceptual.

An issue is described formally as a statement about an aspect of the world. Every issue has at least two outcomes representing the alternative states or possibilities of that aspect of the world. An issue can be phrased as a question, where the mutually exclusive answers to that question form its outcomes. One of the issues – the

[2] Audun Jøsang, *Subjective Logic: A Formalism for Reasoning Under Uncertainty* (Berlin: Springer, 2016).
[3] Simon Pope and Audun Jøsang, "Analysis of Competing Hypothesis Using Subjective Logic," in *10th International Command and Control Research Technology Symposium* (McLean VA: The Department of Defense Command and Control Research Program, 2005).
[4] https://www.houstonwehave.ai/

key issue – represents the question or problem under investigation and may be described as a question or hypothesis rather than a statement. Together the issues represent the universe of discourse about the problem under investigation – the set of factors that need to be considered in answering the question or hypothesis.

For example, in the present analysis, **the key issue** is (see Table 2):

Will the oceans become transparent?

And it is assigned two possible **outcomes**:

The oceans will become transparent
The oceans will not become transparent

Together, these two outcomes exhaust the possibility space for the issue (of course, it is possible to have any number of outcomes > 1, but together they must logically and formally exhaust the possibility space for that issue).

Because we have no *a priori* information about the likelihood of each outcome, they divide the possibility space equally and are each assigned a likelihood of 50%.

The other issues are organised similarly (see Table 2). For example, the **issue**:

System integration

is assigned two possible **outcomes**:

A state will successfully develop the capability to integrate technologies and platforms to create a dense, adaptive sensing mesh
A state will not successfully develop the capability to integrate technologies and platforms to create a dense, adaptive sensing mesh

And again, because we have no *a priori* information about the likelihood of each outcome, they divide the possibility space equally and are each assigned a likelihood of 50%.

Second Step – Creating the Model

The second step in the workflow is to describe how the issues bear one on another, and, ultimately, on the key issue. The key issue may be described as a hypothesis and the relationships among the issues create a model that ultimately bears on the key issue.

For example (see Table 2), we may argue that the issue (let's call it *issue 1* for our discussion here)

Evolution of autonomous platforms for ocean sensing

will bear on the key issue (let's call it *issue 0*)

Will the oceans become transparent?

in the sense that one of the outcomes of issue 1

Developments in the technology of autonomous platforms for ocean sensing will be sufficient to allow the creation of a dense, adaptive sensing mesh

will be a strong positive influence on (that is, a driver of) one of the outcomes of issue 0

The oceans will become transparent

But issue 1 itself may be influenced or driven by other issues. In this example, we propose that another issue (let's call it *issue 2*)

> *Evolution of the science and technology of underwater communication*

bears on issue 1

> *Evolution of autonomous platforms for ocean sensing*

in the sense that one of the outcomes of issue 2

> *Developments in the science and technology of underwater communications will be sufficient to allow autonomous platforms to fully participate in the creation of a dense, adaptive sensing mesh*

will be a strong positive influence on (or a driver of) one of the outcomes of issue 1

> *Developments in the technology of autonomous platforms for ocean sensing will be sufficient to allow the creation of a dense, adaptive sensing mesh*

In this way, we may create a model of the relationships among the issues, creating a hierarchy of relationships bearing down on the key issue. Some issues are influenced by more than one other issue, some issues can influence more than one other issue, and yet others may only influence the key issue.

But we do more than just describe qualitative relationships between the issues. We may make expert judgements, based on our knowledge of the science and technology involved, of the relationships between the issues. Each judgement is of the form:

> If [*an outcome of issue A*] is true, then there is [*a judged likelihood*] that [*an outcome of issue B*] is true

Returning to our examples above, we may judge

> If [*developments in the science and technology of underwater communications will be sufficient to allow autonomous platforms to fully participate in the creation of a dense, adaptive sensing mesh*] is true, then it is [*likely*] that [*developments in the technology of autonomous platforms for ocean sensing will be sufficient to allow the creation of a dense, adaptive sensing mesh*]

In this example, we judge that an outcome of one of our science issues, *Evolution of the science and technology of underwater communication*, bears on an outcome of one of our technology issues, *Evolution of autonomous platforms for ocean sensing*. We further judge that the relationship is *likely*, using the standard meanings of the intelligence community – that there exists a causal relationship that is reasonably strong with about a 75% probability that change in one will elicit change in the other (see Table 3 below which maps the standard meanings of *likely* etc to probabilities).

In this way, we may build up a model whose relationships have expert judgements assigned to them. These judgements may change the probabilities of the outcomes of the issues that they influence – ultimately including the key issue. Using the calculus of subjective logic, we may evaluate these changes in a rigorous and consistent way.

But these are broad judgements based on broad expert knowledge of the issues. In the third step of the assessment process described below, we may add specific opinions about the issues based on actual observations from data sources of judged reliability.

Third Step – Adding Judged Information to the Model

The model may now be enhanced with observations about the issues gleaned from information sources such as scientific papers or even expert commentary. Each information source can be weighted for its reliability, with, for example, peer-reviewed scientific papers from top journals weighted more highly than commentary in a technical blog or magazine. Each observation (there can be several from any single information source) is used to create an opinion about the likelihood of a particular outcome of an issue.

For example, a scientific review about the future of ocean sensing in a top journal could be upbeat enough that we could make an observation about the issue, *Evolution of ocean sensing technology*, and derive an opinion that one of its outcomes, *Developments in ocean sensing technology will be sufficient to allow detection of anomalous masses in the water column*, is *Likely (probability = 75%).*

Final Step – Running the Model and Creating an Assessment

Intelfuze fuses the probabilities of the outcomes of issues, the expert opinions of the likelihoods of the outcomes, and the judgements about their relationships using the calculus of subjective logic. This creates a structured assessment of the likelihood of each of the outcomes of the key issue – that is, the likelihood of the hypothesis being true. The certainty of that likelihood (that is, the confidence we may attach to the likelihood) is also computed independently.

The headline assessment may be unfolded to expose the contributions the various issues and judged information made to the overall assessment. This allows a rigorous examination of the significance and diagnosticity of the issues in play.

The Issues in Play

Initial Scan of the Issues in Play

We considered a wide range of science and technology issues bearing on ocean sensing and the detection of submarines as anomalies in the water column. The issues raised in this scan were across a broad science and technology horizon and were at very different levels of detail. Table 1 summarises the issues that gained the most salience at our workshop.

Table 1: Preliminary Consideration of Issues

Impact of artificial intelligence on ocean monitoring
Artificial intelligence capabilities for real time applications
Asynchronous artificial intelligence capabilities
Constructing libraries of signatures
Exploiting ocean geographies near submarine ports
Developments in environmental modelling
Developments in data fusion
Fusion of civil and military technologies
Detection of the modification of the ocean environment
Impact of sensor technology on ocean monitoring
Evolution of target platforms
Evolution of sensing platforms
Development of sensing technology systems
Developments of stored energy technology systems
Development of tripwires at choke points
Developments in underwater communication
Developments in through-water to air communications
Long range underwater communications
Short range underwater communications

As a result of these discussions, we envisaged a future world ocean that was comprehensively modelled and richly sensed through a dense, adaptive sensing mesh. We considered whether developments in the science of ocean modelling would be sufficient to support the creation of such fine-scaled dynamical systems models, and whether those models would support an adaptive sensing mesh that would discriminate anomalies, such as submarines, in the water column.

Such systems models of the world ocean would be richly parameterised with many more physical, chemical and biological variables than is currently the case.

The adaptive sensing mesh would detect a much wider range of anomalous phenomena including:

- Sonar and acoustic signals
- Magnetic anomaly signals
- Gravitational anomaly signals
- Hydrodynamic pressure wave and wake turbulence signals
- Electro-optical / infra-red / thermal signals
- Radiation and particle signals arising from nuclear reactors
- Chemical signals
- Biological signals

The data from the sensors would be integrated (including with the ocean systems models) in real-time through advanced computing and communication technologies.

The adaptive sensing mesh itself would be built from space platforms, manned and unmanned aerial platforms, manned and unmanned ocean surface platforms, manned and unmanned underwater platforms, and sensors fixed to the ocean bottom.

Re-Interpretation of Issues in Play

We then revised our issues to better reflect our vision of the future of the science and technology of ocean sensing.

Given the long time-horizon, we sought to block the issues into broad areas of science and technology to help us avoid any biases towards today's, as opposed to tomorrow's, science and technology. We sought those broad areas of science which, as they progress, will allow the development of new or improved sensing technologies, and those broad areas of technology which, as *they* progress, will use new science to create new or improved sensing technologies.

This growing suite of new science and technology needs to be organised, managed, integrated and deployed for it to be effective. Thus the capability for systems integration is itself an issue.

And potential local differences in ocean geography may exist to the extent that some states may be denied the opportunity to deploy sensors in some parts of the world ocean, and some states may have adverse local geographies that make sensing their submarines much easier. Thus the geography of the oceans is also an irreducible issue.

Finally, we thought that the response of future submarines to future sensing technologies – the science and technology of counter-detection – needed to be considered as an issue in itself.

Unpacking the Issues

Table 2 shows the issues in play. It includes the key issue – Will the oceans become transparent? – the hypothesis under test. Appendix 1 shows the issues as organised in the *Intelfuze* system.

Apart from the key issue, there are two broad issues to do with the context of the science and technology – the matter of system integration, and the matter of the particular geographies of the ocean. And there are folders for high-level science and technology issues, including counter-detection technologies.

The issues are each described in terms of their possible outcomes. In this preliminary analysis we've cleaved to simplicity and described only two outcomes for each issue, and they are each assigned *a priori* likelihoods of 0.5, so together exhausting the possibility space (Appendix 1).

Table 2: The Issues in Play (The Universe of Discourse)

Issue	Description
The key issue	
Will the oceans become transparent?	The extent to which the world ocean will become transparent as a result of developments in science and technology to about 2050
Contextual issues	
System integration	The extent to which a state has the industrial, technical etc capability to integrate technologies and platforms to create a dense, adaptive sensing mesh
Geography of the oceans	The extent to which deeper knowledge of particular geographies can amplify the effectiveness of ocean sensing
Science issues	
Evolution of the science of ocean modelling	The extent to which developments in the science of ocean modelling will evolve to allow the creation of a fine-scale dynamical systems models of the physical, chemical and biological attributes of the world ocean
Evolution of computer science and information technology	The extent to which developments in computer science and information technology will evolve to support the key computational needs of ocean sensing
Evolution of the science and technology of underwater communication	The extent to which fundamental developments in the science and technology of underwater communication will evolve to allow the creation of a dense, adaptive sensing mesh
Evolution of new sensors	The extent to which new sensors based on new science to exploit new sensing channels, such gravimetric, magnetic, optical, chemical and particle physics channels
Technology issues	
Evolution of ocean sensing technology	The extent to which developments in ocean sensing technology will evolve to allow the detection of anomalous masses in the water column
Evolution of autonomous platforms for ocean sensing	The extent to which developments in autonomous platforms for ocean sensing will evolve to allow the creation of a dense, adaptive sensing mesh
Evolution of battery technology	The extent to which developments in battery and other stored energy technologies will evolve to allow effective autonomous sensing platforms, ocean sensing, computation and communication
Evolution of counter-detection technologies	The extent to which advances in the science and technology of counter-detection – accelerated by within-state competition between submarine and ASW designers – will allow submarines to avoid detection

Creating the *Intelfuze* Model

After describing the issues in play as the universe of discourse, we created a model of the relationships between them in workshop discussion.

The Model Structure

Figure 1 below shows the relationships among the issues that form the model. Appendix 2 shows the model as organised in the *Intelfuze* system.

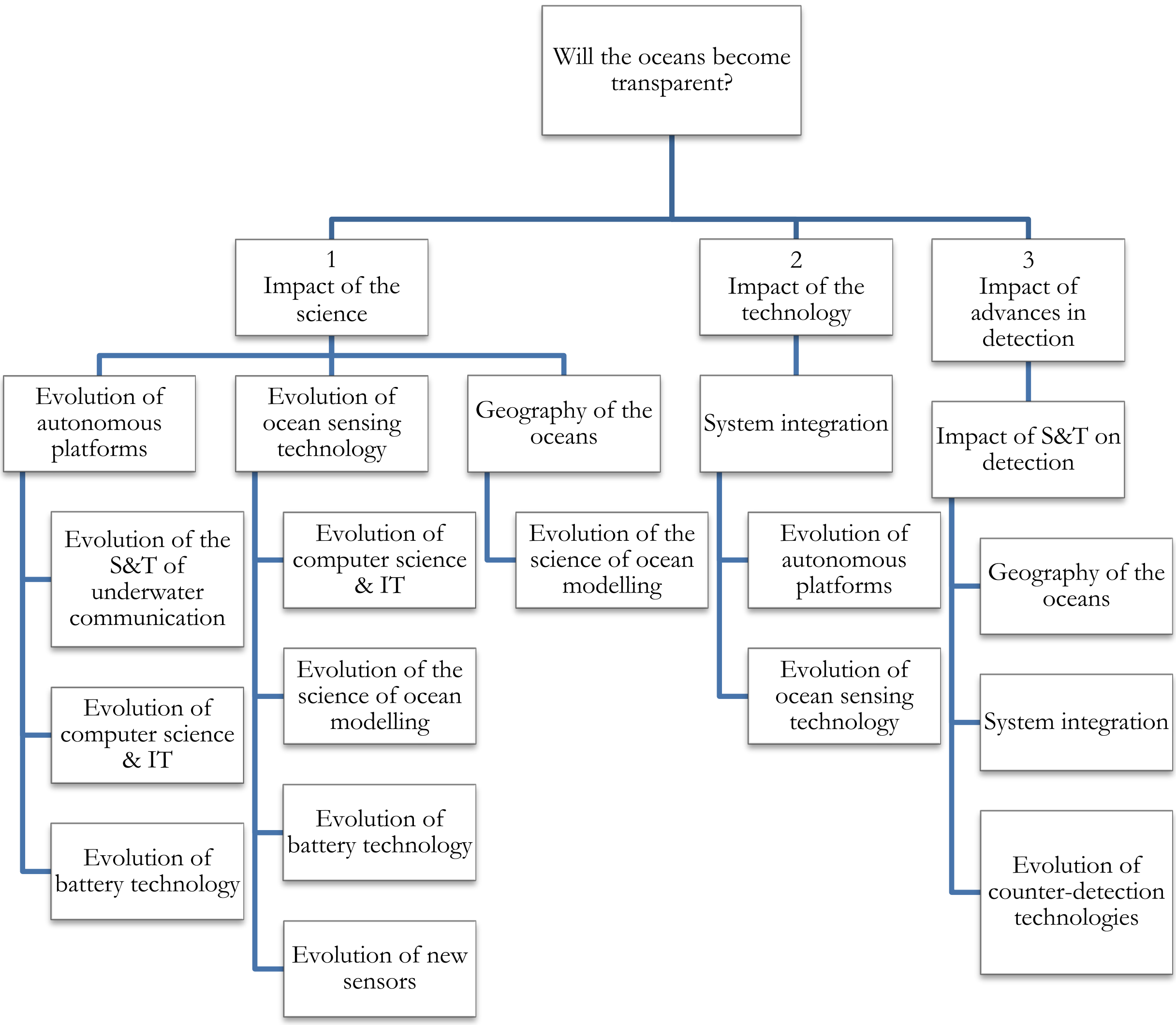

Figure 1: The assessment model

The issues are represented as boxes with the key issue the top box in the figure. Issues drive the issues above them creating a cascade of influences on the key issue at the top. The three numbered boxes below the key issue are not issues themselves but the execution phases of the model.

This model is organised in three execution phases allowing the impact of, say, *issue A* on *issue B* to be evaluated before the impact of *issue B* on *issue C*. Thus the influence of the *Evolution of computer science & IT* on the *Evolution of autonomous platforms* is evaluated in execution phase *1 Impact of the science* before the influence of the *Evolution of autonomous platforms* on *System integration* is evaluated in execution phase *2 Impact of the technology*.

Expert Judgements about Relationships in the Model

We assigned expert judgements on the influence of one issue on another based on our knowledge of the science and technology involved. We strove to be very conservative in these judgements given the decades-long time frame we are dealing with. We used the standard terminology and probabilities of intelligence analysis.

As Table 3 shows, the spread of probabilities from 0 to 1 are mapped to a set of common English words in Western intelligence analysis. We calculate the probabilities exactly in *Intelfuze*, even though the input values for the calculations are estimates. So we prefer to use the simple English descriptors rather than the numerical values. We do not wish our judgements to suffer from spurious quantification – to be cloaked in a mantle of numerical respectability creating a false sense of scientific precision.

In general, we judged areas of science and technology that have made rapid strides over the last few decades and also shown no signs of tapering off to be *very likely* (p = 90%) to influence or drive other issues in the model. Examples of such areas are *Computer science and information technology* and *Geography of the oceans*. On the other hand, we judged those areas of science and technology that have made steady progress over the last few decades, but with no game-changing discoveries, to be *likely* (p = 75%) to influence other issues in the model. Examples of such areas are the *Science and technology of underwater communication* and *Battery technology*.

Table 4 shows the judgements we made. Appendix 2 shows the judgements as organised in the *Intelfuze* system.

Table 3: Standard terminology for likelihood and reliability

Descriptor	Probability	Range
Likelihood		
Absolutely not	0%	Exactly 0%
Almost never	0.01%	0% - 0.5%
Extremely unlikely	1%	0.5% - 5.5%
Very unlikely	10%	5.5% - 16.25%
Unlikely	22.5%	16.25% - 28.75%
Somewhat unlikely	35%	28.75% - 42.5%
Chances about even	50%	42.5% - 57.5%
Somewhat likely	65%	57.5% - 71.25%
Likely	77.5%	71.25% - 83.75%
Very likely	90%	83.75% - 94.5%
Extremely likely	99%	94.5% - 99.5%
Almost always	99.99%	99.5% - 100%
Absolutely	100%	Exactly 100%
Reliability		
Completely unreliable	0%	Exactly 0%
Very unreliable	5%	0% - 15%
Somewhat unreliable	25%	15% - 37.5%
Somewhat reliable	50%	37.5% - 62.5%
Fairly reliable	75%	62.5% - 85%
Highly reliable	95%	85% - 99.9%
Completely reliable	100%	99.9%- 100%

Table 4: The judged likelihoods of one issue influencing another in the model

This outcome …	… of this issue …	… influences this outcome of the issue below …	… with this probability …	expressed as this likelihood
Impact of the science				
		… on the issue of the evolution of autonomous platforms for ocean sensing		
Developments in the science and technology of underwater communications will be sufficient to allow autonomous platforms to fully participate in the creation of a dense, adaptive sensing mesh	Evolution of the science and technology of underwater communication	Developments in the technology of autonomous platforms for ocean sensing will be sufficient to allow the creation of a dense, adaptive sensing mesh	75%	Likely
Developments in computer science and information technology will be sufficient to support advances in ocean sensing in the broad	Evolution of computer science and information technology		90%	Very likely
Developments in battery technology will be sufficient to support the power needs of a dense, adaptive sensing mesh	Evolution of battery technology		75%	Likely
		… on the issue of the evolution of ocean sensing technology		
Developments in computer science and information technology will be sufficient to support advances in ocean sensing in the broad	Evolution of computer science and information technology	Developments in ocean sensing technology will be sufficient to allow detection of anomalous masses in the water column	90%	Very likely
Developments in the science of ocean modelling will be sufficient to create fine-scale dynamical systems models of the world ocean	Evolution of the science of ocean modelling		75%	Likely
Developments in battery technology will be sufficient to support the power needs of a dense, adaptive sensing mesh	Evolution of battery technology		75%	Likely
Sensors based on new science will be sufficient to detect the next generation of quiet, stealthy submarines	Evolution of new sensors		90%	Very likely

Table 4 (continued)

This outcome …	**… of this issue …**	**… influences this outcome of the issue below …**	**… with this probability …**	**expressed as this likelihood**
		… on the issue of the geography of the oceans		
Developments in the science of ocean modelling will be sufficient to create fine-scale dynamical systems models of the world ocean	Evolution of the science of ocean modelling	Deeper knowledge of particular geographical features of the world ocean will amplify the effectiveness of ocean sensing	75%	Likely
Impact of the technology		***… on the issue of system integration***		
Developments in the technology of autonomous platforms for ocean sensing will be sufficient to allow the creation of a dense, adaptive sensing mesh	Evolution of autonomous platforms for ocean sensing	A state will successfully develop the capability to integrate technologies and platforms to create a dense, adaptive sensing mesh	75%	Likely
Developments in ocean sensing technology will be sufficient to allow detection of anomalous masses in the water column	Evolution of ocean sensing technology		75%	Likely
Impact of advances in detection		***… on the key issue: Will the oceans become transparent?***		
Deeper knowledge of particular geographical features of the world ocean will amplify the effectiveness of ocean sensing	Geography of the oceans	The oceans will become transparent	90%	Very likely
A state will successfully develop the capability to integrate technologies and platforms to create a dense, adaptive sensing mesh	System integration		90%	Very likely
Developments in counter-detection technology will be sufficient to allow submarines to avoid detection	Evolution of counter-detection technologies	The oceans will not become transparent	75%	Likely

Adding Judged Information to the Model

The *Intelfuze* process now allows for the introduction of data into the model. In line with the approach of subjective logic, this introduction of data into the model is a two-step process.

First, we make an observation about an issue from an information source. For example, we may make an observation about the *System integration* issue from a scientific paper concerning progress in integrating underwater robots and deep-sea sensors. We may assign a level of reliability to the information source (see Table 3). For example, we may assign a reliability of 95% (*Highly reliable*) to a peer-reviewed scientific journal paper, but only a reliability of 65% (*Fairly reliable*) to a foreign government report.

Second, we offer an (expert) opinion (an implication from the observation) on an outcome of the issue. This parallels the way in which we offered judgements on the links between issues when we built the model above. For example, from our observation from the scientific paper above, we may form the opinion that it is *Very likely* (p = 90%) that the outcome for that issue will be *A state will successfully develop the capability to integrate technologies and platforms to create a dense, adaptive sensing mesh*.

In this study, we sought from the scientific and technical literature a representative collection of reliable papers covering the issues. It was not intended to be an exhaustive literature review, given time and resource limitations, but rather a fair sample of a burgeoning field. We were often able to make observations about more than one issue from a single paper.

Table 5 lists the scientific and technical papers used as information sources in the analyses. And Table 6 presents a summary of the papers, observations and opinions. We assigned a reliability of 95% (*Highly reliable*) to peer-reviewed scientific papers and 85% (*Highly reliable*) to less formal, but still valuable publications from think-tanks, technical magazines and the like.

Table 5: The scientific and technical papers used as information sources

Spencer Ackerman, “Robots, Deep-Sea Sensors Help Pentagon Futurists Hunt Subs,” *Wired,* April 3, 2013. https://www.wired.com/2013/04/darpa-subs/.

Alberto Alvarez, “Volumetric Reconstruction of Oceanographic Fields,” *IEEE Journal of Oceanic Engineering* 36, (2011): 13-25, DOI 10.1109/JOE.2010.2092472.

Scott Bainbridge, “Detection of Trace Levels of Hydrocarbons in Sea Water,” Australian Institute of Marine Science, 2019.

John R. Benedict “The Unraveling and Revitalization of US Navy Antisubmarine Warfare.” *Naval War College Review* 58, no. 2 (2005): https://digital-commons.usnwc.edu/nwc-review/vol58/iss2/6.

Germain Boussarie, “Environmental DNA Illuminates the Dark Diversity of Sharks,” *Science Advances* 4, no. 5 (2018): https://advances.sciencemag.org/content/4/5/eaap9661/tab-pdf.

Peter Brodsky and Jim Luby, “Flight Software Development for the Liberdade Flying Wing Glider,” Applied Physics Laboratory, University of Washington, 2013, https://apps.dtic.mil/dtic/tr/fulltext/u2/a602311.pdf.

Jonathan Burns, “Remote Detection of Undeclared Nuclear Reactors Using the WATCHMAN Detector,” *NuPhys2017, Prospects in Neutrino Physics* (London: NuPhys2017-Burns, 2018): https://arxiv.org/pdf/1804.00655.pdf.

John Carroll et al, “Monitoring Reactor Anti-Neutrinos Using a Plastic Scintillator Detector in a Mobile Laboratory,” *arXiv*, 2018, https://arxiv.org/abs/1811.01006.

Bryan Clark, *The Emerging Era in Undersea Warfare* (Washington DC: Center for Strategic and Budgetary Assessments, 2015).

Owen R. Cote Jr., “Invisible Nuclear-Armed Submarines, or Transparent Oceans? Are Ballistic Missile Submarines Still the Best Deterrent for the United States?” *Bulletin of the Atomic Scientists* 75 (2019): 30-35, DOI: 10.1080/00963402.2019.1555998.

Emrecan Demirors et al, “Software-Defined Underwater Acoustic Networks: Toward a High-Rate Real-Time Reconfigurable Modem,” *IEEE Communications Magazine* 53, no. 11 (2015): 64-71, https://ieeexplore.ieee.org/document/7321973.

Jonathan Gates, “Is the SSBN Deterrent Vulnerable to Autonomous Drones?” *The RUSI Journal* 161, no. 6 (2016): 28-35, https://doi.org/10.1080/03071847.2016.1265834.

David Hambling, “The Inescapable Net: Unmanned Systems in Anti-Submarine Warfare,” British American Security Information Council, 2016, https://basicint.org/publications/david-hambling/2016/inescapable-net-unmanned-systems-anti-submarine-warfare.

Carol Naughton and Sebastian Brixey-Williams, “Impact of Emerging Technologies on the Future of SSBNs,” British American Security Information Council, 2016, https://basicint.org/wp-content/uploads/2018/06/Pugwash_SSBNs_ConferenceReport_v8.pdf.

Ki-Hong Park et al, “Underwater Wireless Communications and Networking," *IEEE Access* 6 (2018): 52288-52294.

Daniel L. Rudnick, “Ocean research enabled by underwater gliders,” *Annual Review of Marine Science* 8 (2016): 519–541.

Table 6: Summary of observations and opinions about the issues and their outcomes

Issue	***Outcome***	**Observation from a paper**	**Reliability of paper**	**Opinion on outcome**
System integration	*A state will successfully develop the capability to integrate technologies and platforms to create a dense, adaptive sensing mesh*			
		Ackerman (2013)	Highly reliable (85%)	Very likely (90%)
		Benedict (2005)	Highly reliable (95%)	Very likely (90%)
Geography of the oceans	*Deeper knowledge of particular geographical features of the world ocean will amplify the effectiveness of ocean sensing*			
		Alvarez (2011)	Highly reliable (95%)	Very likely (90%)
		Clark (2015)	Highly reliable (85%)	Very likely (90%)
		Cote (2019)	Highly reliable (95%)	Very likely (90%)
Evolution of the science of ocean modelling	*Developments in the science of ocean modelling will be sufficient to create fine-scale dynamical systems models of the world ocean*			
		Alvarez (2011)	Highly reliable (95%)	Very likely (90%)
		Clark (2015)	Highly reliable (85%)	Very likely (90%)
		Rudnick (2016)	Highly reliable (95%)	Very likely (90%)
Evolution of computer science and information technology	*Developments in computer science and information technology will be sufficient to support advances in ocean sensing in the broad*			
		Clark (2015)	Highly reliable (85%)	Very likely (90%)
		Hambling (2016)	Highly reliable (85%)	Very likely (90%)
Evolution of the science and technology of underwater communication	*Developments in the science and technology of underwater communications will be sufficient to allow autonomous platforms to fully participate in the creation of a dense, adaptive sensing mesh*			
		Clark (2015)	Highly reliable (85%)	Very likely (90%)
		Demirors (2015)	Highly reliable (85%)	Very likely (90%)
		Hambling (2016)	Highly reliable (85%)	Very likely (90%)
		Park (2018)	Highly reliable (95%)	Very likely (90%)

Table 6 (continued)

Issue	***Outcome***	**Observation from a paper**	**Reliability of paper**	**Opinion on outcome**
Evolution of new sensors	*Sensors based on new science will be sufficient to detect the next generation of quiet, stealthy submarines*			
		Bainbridge (2019)	Highly reliable (95%)	Very likely (90%)
		Boussarie (2018)	Highly reliable (95%)	Very likely (90%)
		Burns (2018)	Highly reliable (90%)	Somewhat likely (65%)
		Carroll (2018)	Highly reliable (90%)	Somewhat likely (65%)
		Clark (2015)	Highly reliable (85%)	Very likely (90%)
		Hambling (2016)	Highly reliable (85%)	Very likely (90%)
Evolution of ocean sensing technology	*Developments in ocean sensing technology will be sufficient to allow detection of anomalous masses in the water column*			
		Clark (2015)	Highly reliable (85%)	Very likely (90%)
		Naughton, Brixey-Williams (2016)	Highly reliable (85%)	Very likely (90%)
Evolution of autonomous platforms for ocean sensing	*Developments in the technology of autonomous platforms for ocean sensing will be sufficient to allow the creation of a dense, adaptive sensing mesh*			
		Brodsky, Luby (2013)	Highly reliable (90%)	Very likely (90%)
		Gates (2016)	Highly reliable (95%)	Somewhat likely (65%)
		Hambling (2016)	Highly reliable (85%)	Very likely (90%)
Evolution of battery technology	*Developments in battery technology will be sufficient to support the power needs of a dense, adaptive sensing mesh*			
		Clark (2015)	Highly reliable (85%)	Very likely (90%)
Evolution of counter-detection technologies	*Developments in counter-detection technology will be sufficient to allow submarines to avoid detection*			
		Clark (2015)	Highly reliable (85%)	Likely (75%)
		Cote (2019)	Highly reliable (95%)	Likely (75%)
Evolution of counter-detection technologies	*Developments in counter-detection technology will not be sufficient to allow submarines to avoid detection*			
		Hambling (2016)	Highly reliable (85%)	Likely (75%)

Assessments from the Model

The *Intelfuze* system gives the user a lot of flexibility in computing assessments from the model. For example, assessments can be run excluding some sources or by excluding some issues to critically evaluate their salience. Also, the impact of some discrete limbs of the model (see Figure 1 and Appendix 2) may be assessed, with their 'top' issue considered as the key issue or hypothesis.

Our assessments here concentrated on the full model, with all issues and all information sources included, to create, in the first instance, a headline assessment of the hypothesis – *The oceans will become transparent* – from the key issue: *Will the oceans become transparent?*

But the full model described the problem from a Western, particularly US, perspective with allowance made for the concomitant developments in counter-detection technology,[5] and for the geography of the oceans that has been generally favourable to the West but not to its adversaries.[6]

We ran three subsidiary assessments to help consider these issues.

- To examine the matter from the perspective of an adversary of the West, we ran an assessment that excluded the impact of geography. This assumes that an adversary will not be able to harvest the advantages for detection that come with a favourable geography as well as the West can. Formally, we assigned a probability of 50% (*Chances about even*) to the effect of each outcome of the *Geography of the oceans* issue to the outcomes of the key issue.
- Similarly, to examine the salience of the evolution of counter-detection technologies, we excluded the impact of the counter-detection issue by making a neutral judgement on its effect on the key issue. Formally, we assigned a probability of 50% (*Chances about even*) to the effect of each outcome of the *Evolution of counter-detection technologies* issue to the outcomes of the key issue.
- And to examine the impact of no advantageous geography and no progress in counter-detection technologies – a possible future for adversaries of the West – we ran an assessment excluding both.

Table 7 shows the headline assessments for each of the four scenarios.

Appendix 3 shows the top levels of the main assessment results as organised in the *Intelfuze* system.

[5] Bryan Clark, *The Emerging Era in Undersea Warfare* (Washington DC: Center for Strategic and Budgetary Assessments, 2015).
[6] John R. Benedict "The Unraveling and Revitalization of US Navy Antisubmarine Warfare." Naval War College Review 58, no. 2 (2005): https://digital-commons.usnwc.edu/nwc-review/vol58/iss2/6.

Table 7: Headline assessment results – Will the oceans become transparent?

Outcome	Likelihood	Certainty
The oceans will become transparent (All issues considered)	Likely (p = 80%)	Somewhat certain (p = 79%)
The oceans will become transparent (With no advantageous geography)	Somewhat likely (p = 71%)	Somewhat uncertain (p = 70%)
The oceans will become transparent (With no progress in the counter-detection issue)	Very likely (p = 88%)	Somewhat certain (p = 77%)
The oceans will become transparent (With no progress in the counter-detection issue, and no advantageous geography)	Likely (p = 83%)	Somewhat uncertain (p = 65%)

Discussion

The results are strong and clear (Table 7). The key result is that the oceans are, in most circumstances, at least *likely* and, from some perspectives, *very likely* to become transparent by the 2050s. This suggests that, despite progress in counter-detection technologies, SSBNs will be able to be detected in the world ocean because of the evolution of science and technology.

These results are universal in the sense that it is *likely* that the ocean will be transparent for any sufficiently advanced state by the 2050s. The historical advantages of the West in both detection and counter-detection will fade.

From the perspective of the West, with its inherent geographical advantages, the probability that it will be able to detect its adversaries (who may not have made effective progress in counter-detection) rises to *very likely*.

From the perspective of the West's adversaries, without the geographical advantage, the probability of being able to detect Western SSBNs reduces slightly to *somewhat likely*. But if the West doesn't make progress in counter-detection, this probability rises to *likely*.

And there are two strong implications from these results.

The first is that the favourable geographies that the West took advantage of in the Atlantic during the Cold War and more recently in the Pacific in its strategic rivalry with China will not have the same salience in the 2050s as then. The evolution of science and technology is likely to make the oceans broadly transparent so that the strategic importance of geographic chokepoints in the ocean is likely to decline.

The second is that the evolution of counter-detection technologies will not have the same salience in the 2050s as it did in earlier times. Over the duration of the Cold War, Western submarines were able to reduce their detectability, at least acoustically, by some orders of magnitude. By the 2050s, our assessments show, progress in counter-detection will only reduce the probability of detection from *very likely* to *likely*. This is nothing like the reductions gained in earlier times, and insufficient to prevent the oceans becoming broadly transparent.

Tomorrow's ocean sensing capabilities will cover a wide range of physical, chemical and biological domains, as discussed above in *Initial scan of the issues in play*. Even allowing for a generous assumption of progress in counter-detection in our models, we cannot see how counter-detection can possibly be as effective in the 2050s as it is today. We are forced to conclude that the coming counter-detection task may be insuperable.

Acknowledgements

The authors are grateful for very helpful discussions with Bryan Clark of the Center for Strategic and Budgetary Assessments in Washington, DC and Rear Admiral (rtd) John Gower CB OBE in London.

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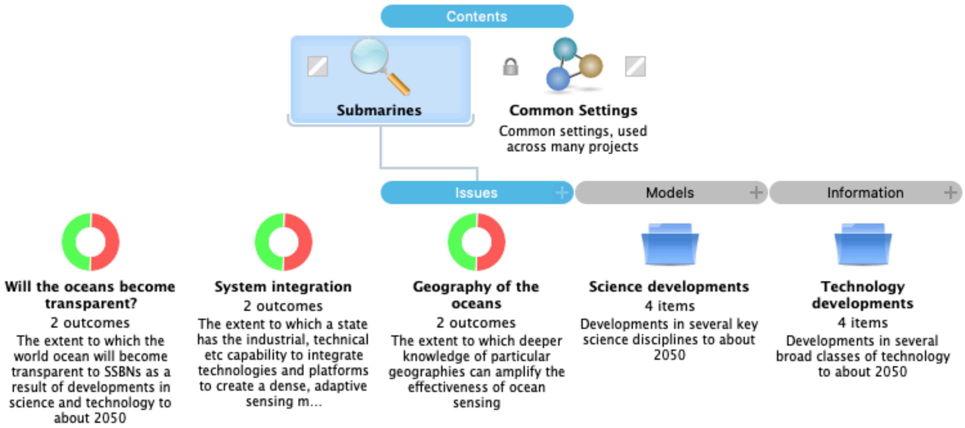
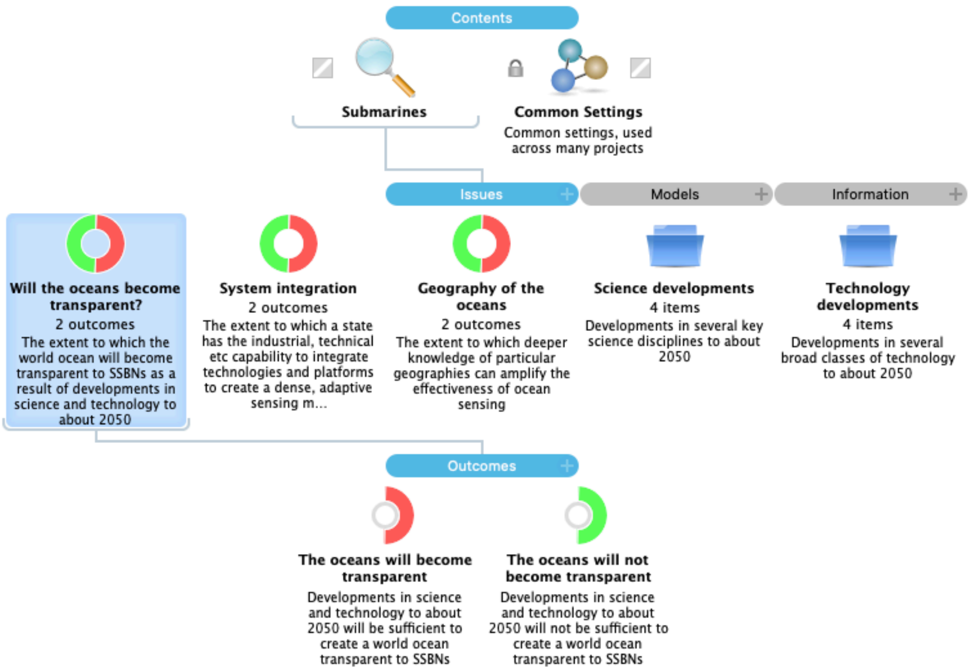
Appendix 1

The Issues in Play (The Universe of Discourse)

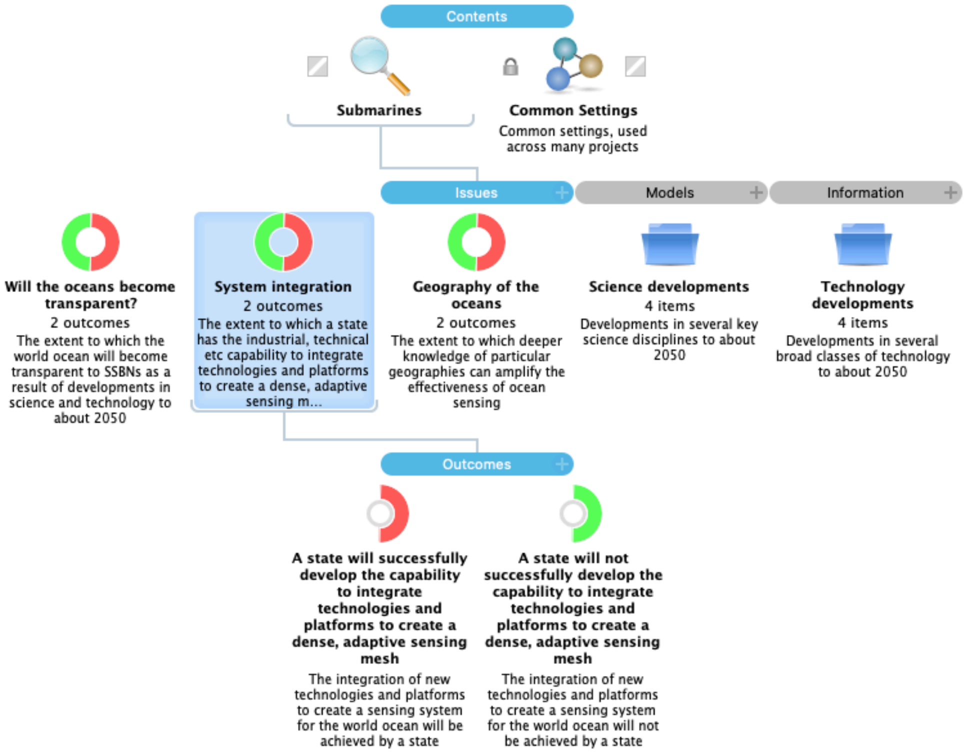
Some screen shots of the issues in play as organised in the *Intelfuze* system are shown below.



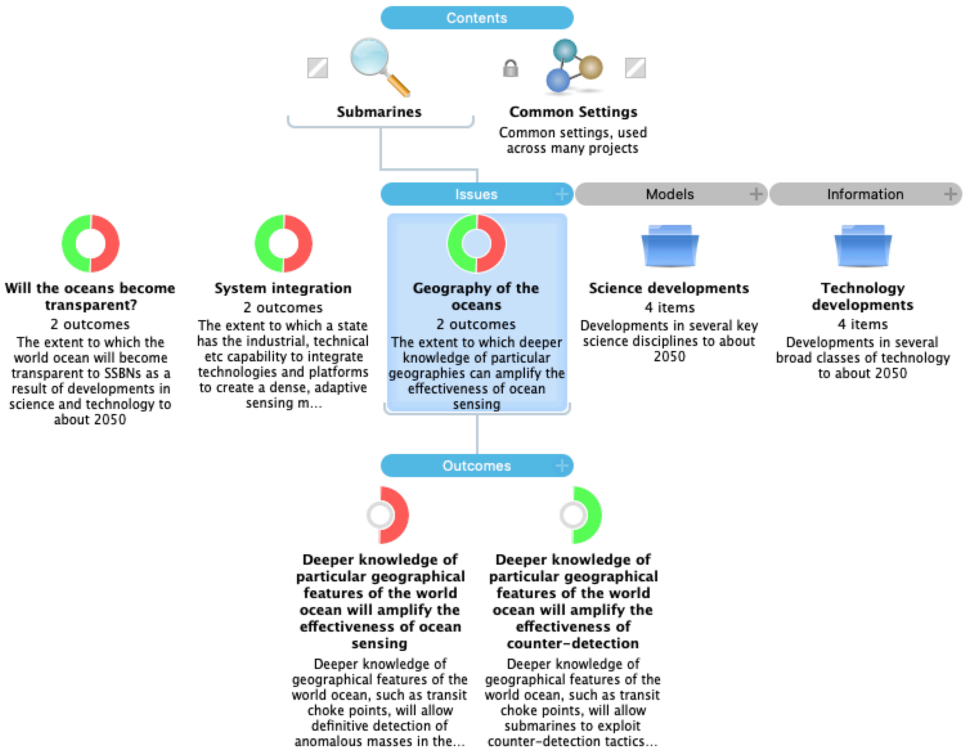
1.1 The issues in play



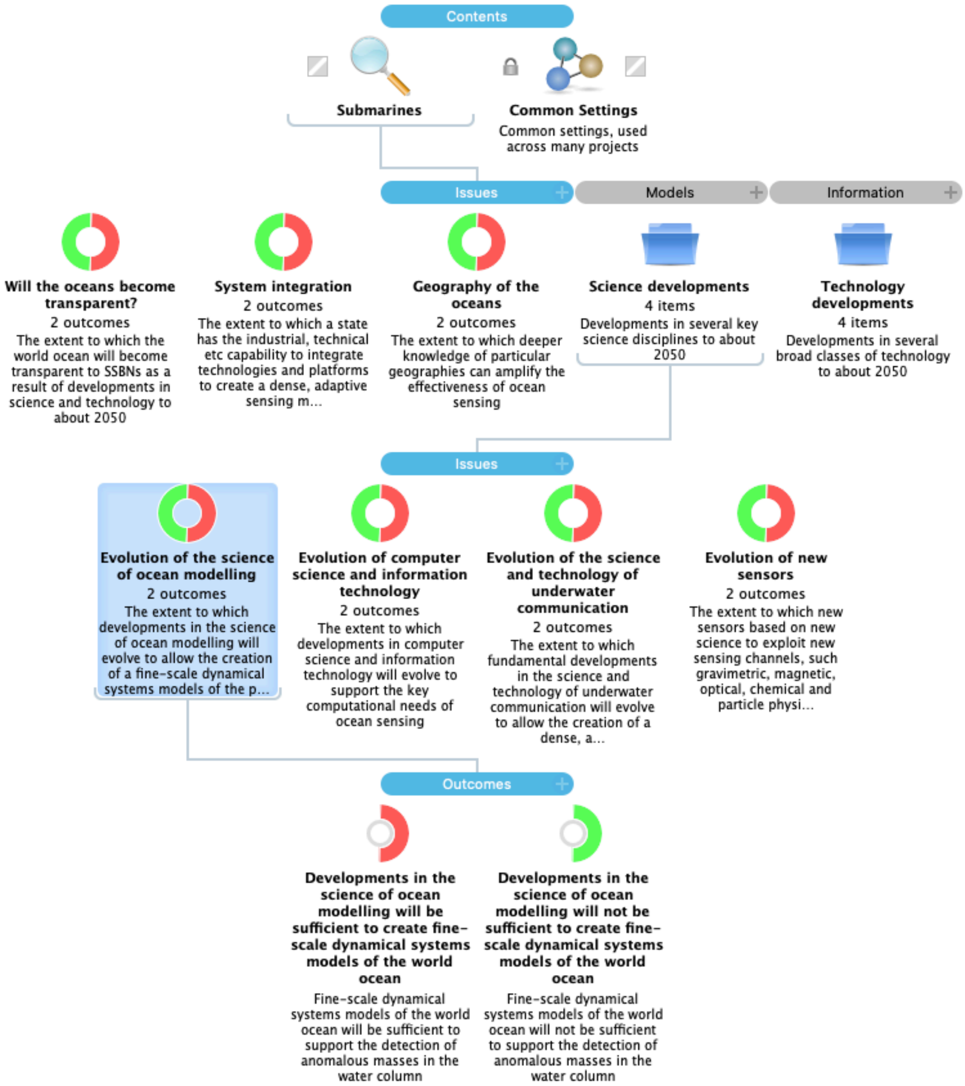
1.2 The key issue and its two *a priori* possibilities



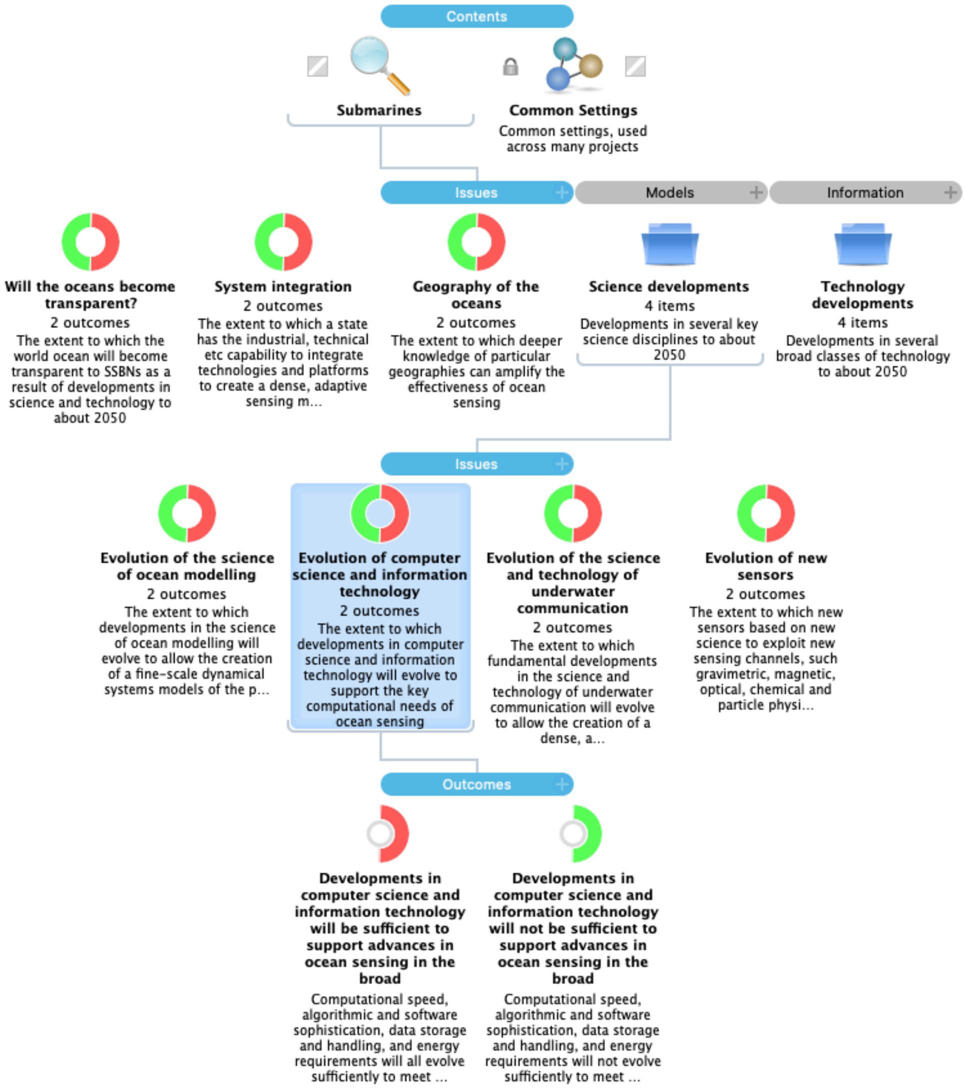
1.3 The system integration issue and its two *a priori* possibilities



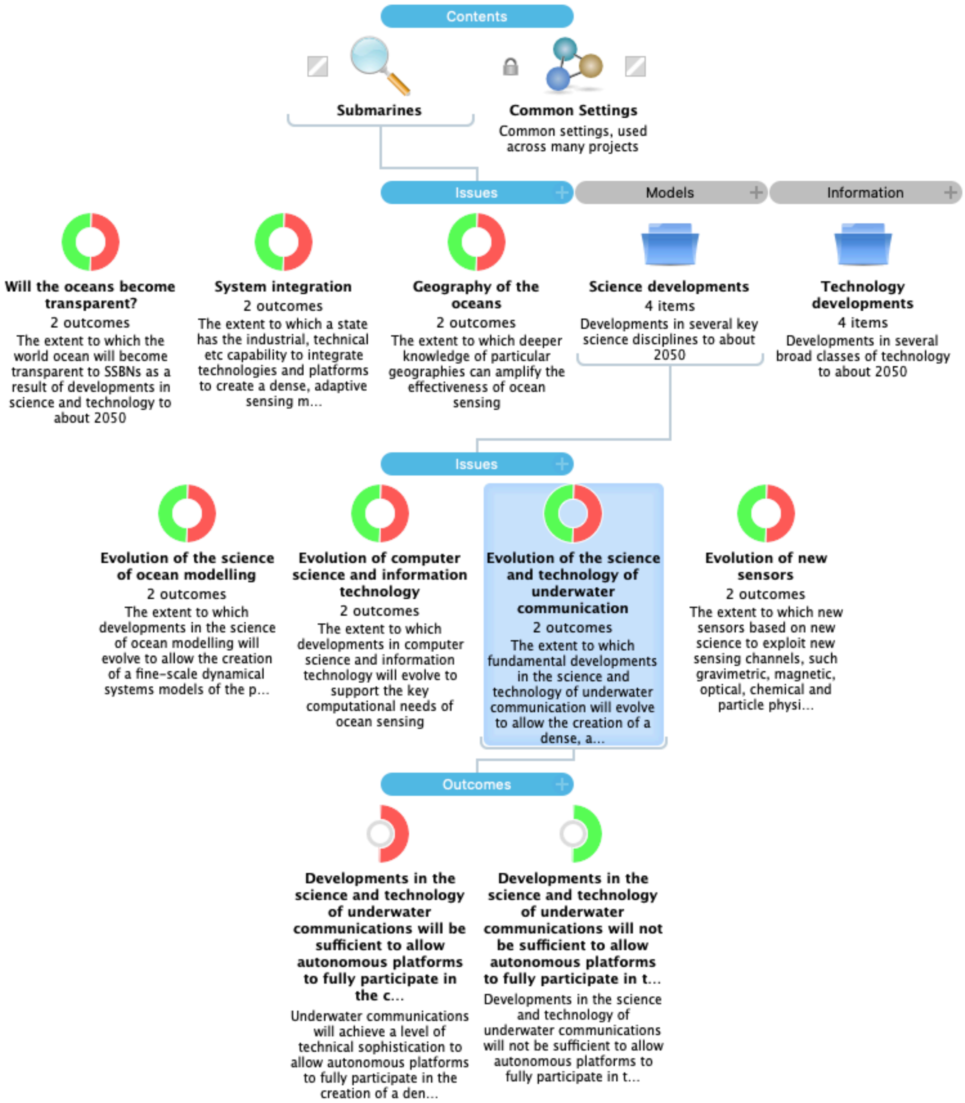
1.4 The issue of the geography of the oceans and its two *a priori* possibilities



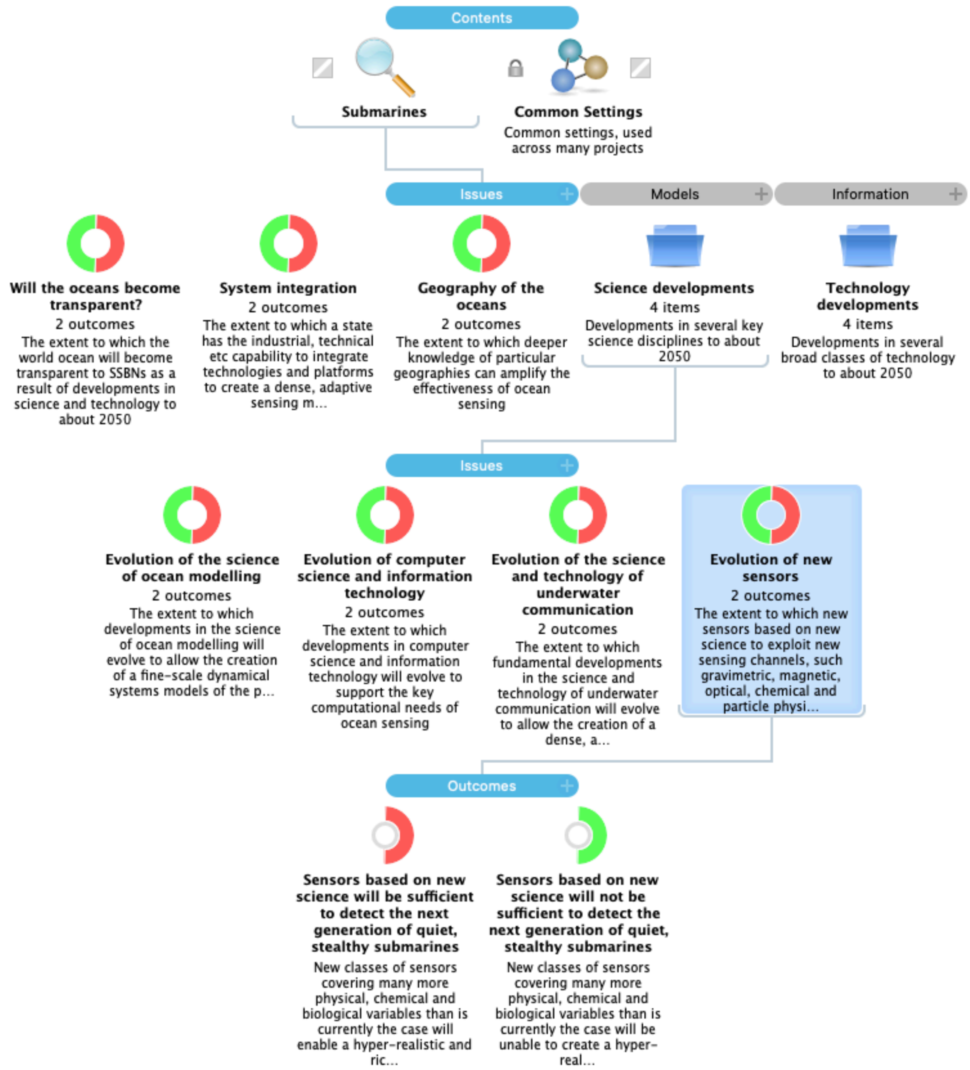
1.5 The issue of the science of ocean modelling and its two a priori possibilities



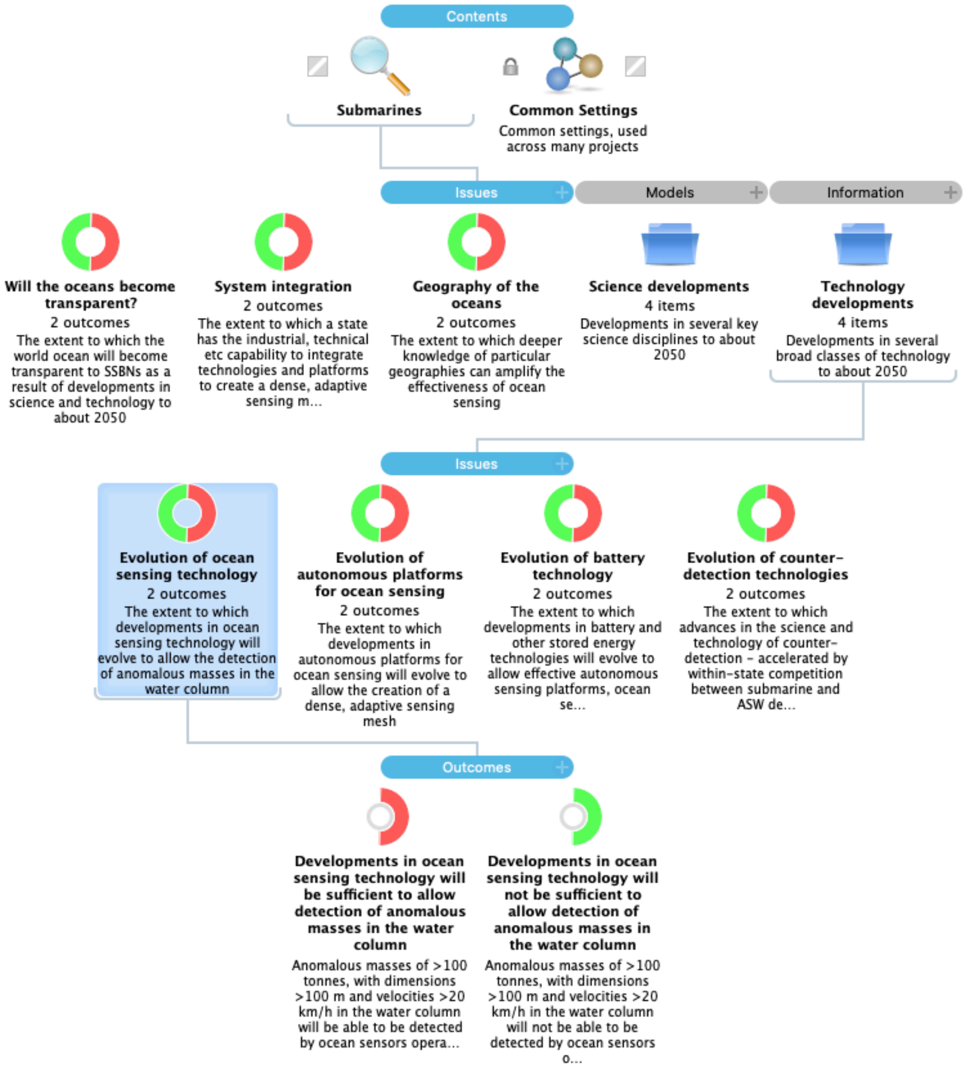
1.6 The issue of computer science and information technology and its two *a priori* possibilities



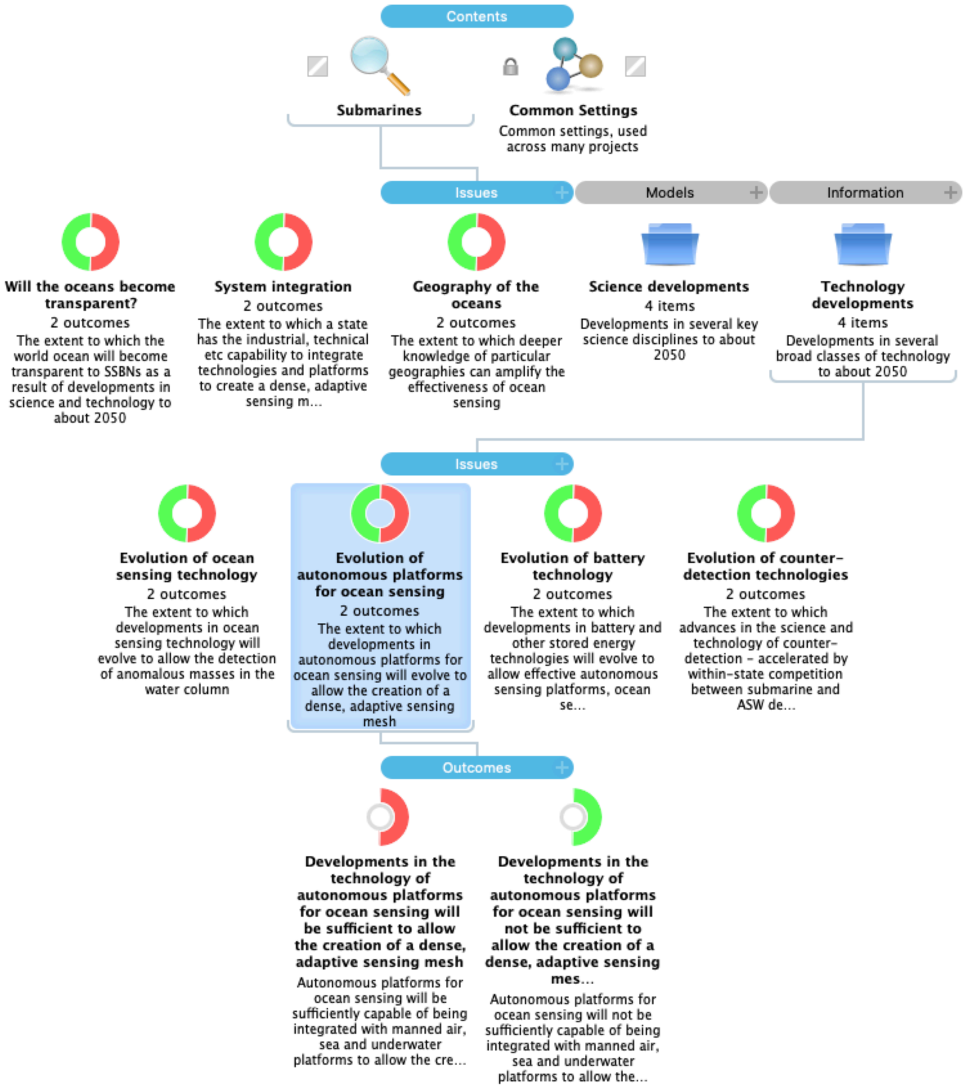
1.7 The issue of science and technology of underwater communications and its two *a priori* possibilities



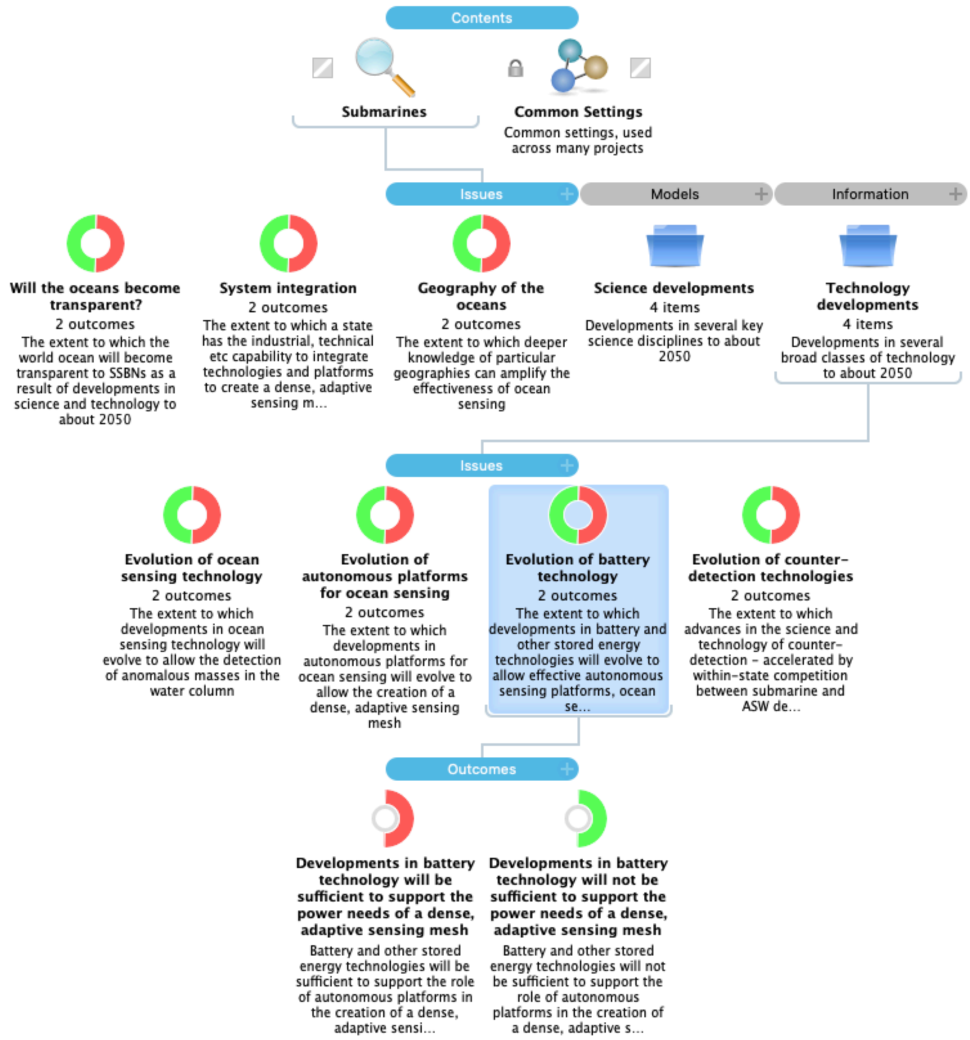
1.8 The issue of new sensors and its two *a priori* possibilities



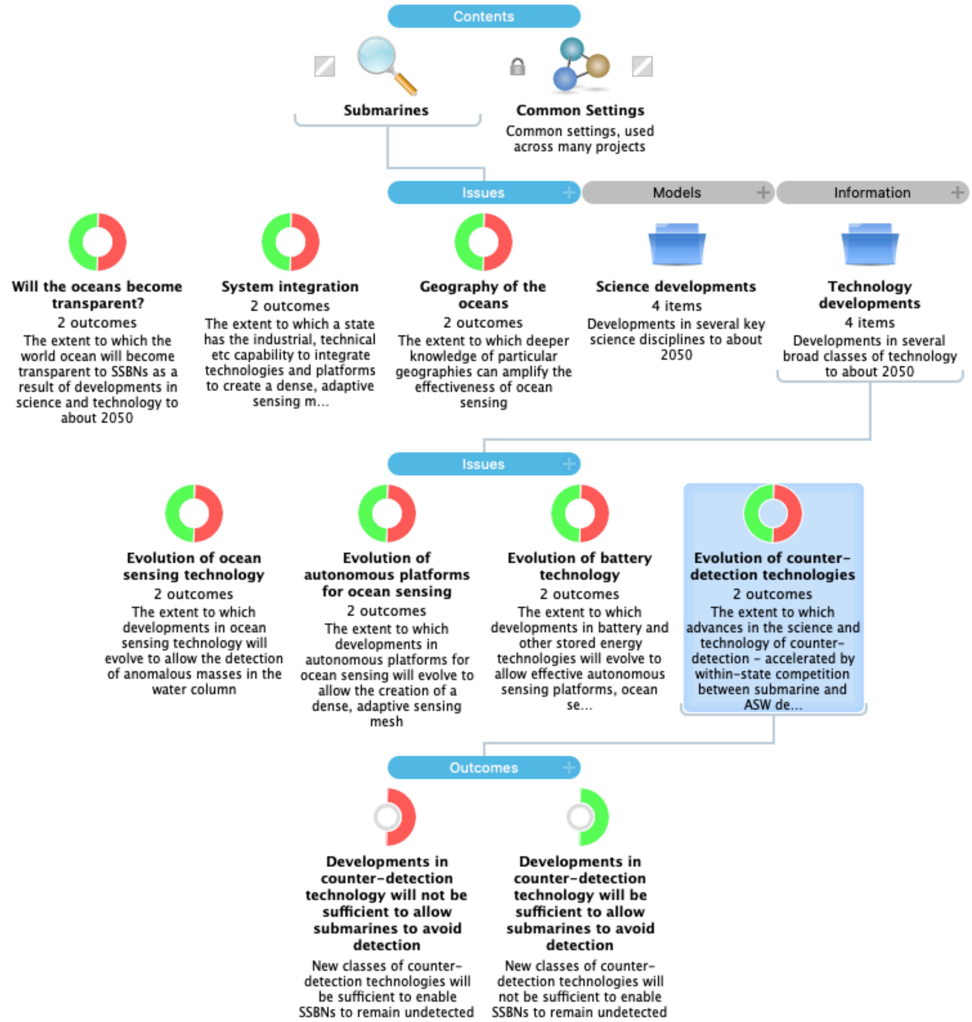
1.9 The issue of ocean sensing technology and its two *a priori* possibilities



1.10 The issue of autonomous platforms technology and its two *a priori* possibilities



1.11 The issue of battery technology and its two *a priori* possibilities

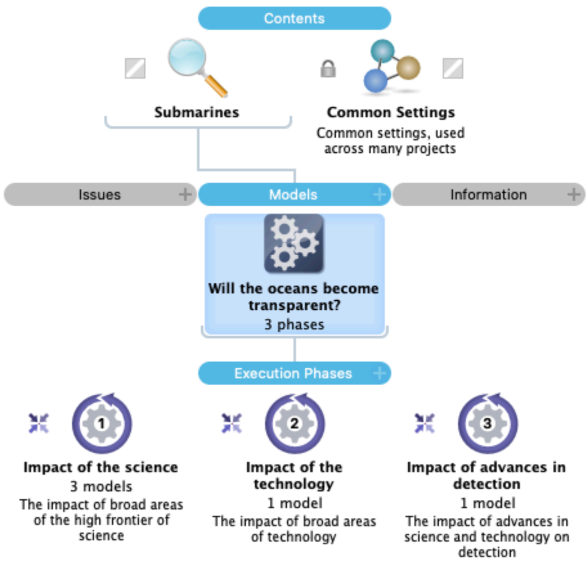


1.12 The issue of counter-detection technologies and its two *a priori* possibilities

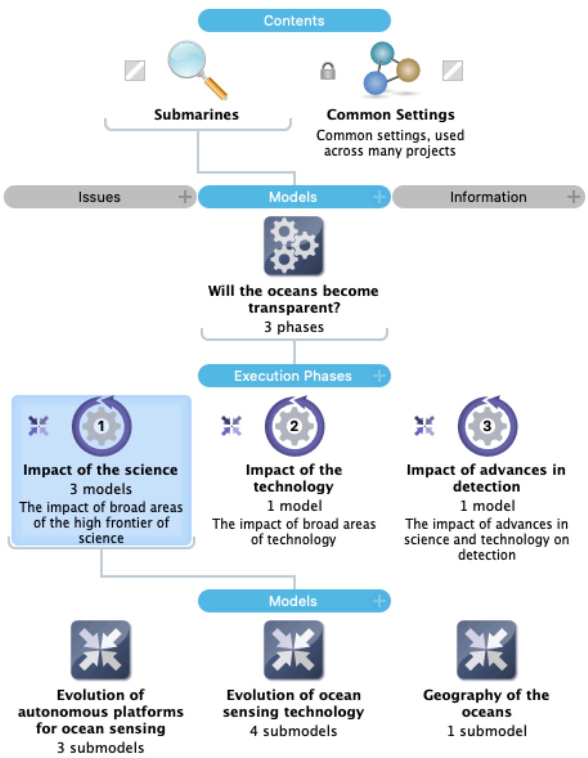
Appendix 2

The Assessment Model

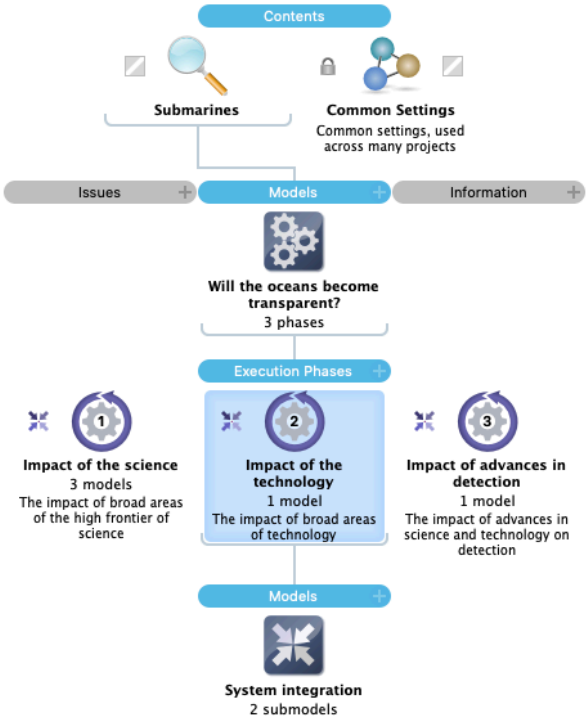
Some screen shots of the model as organised in the *Intelfuze* system are shown below.



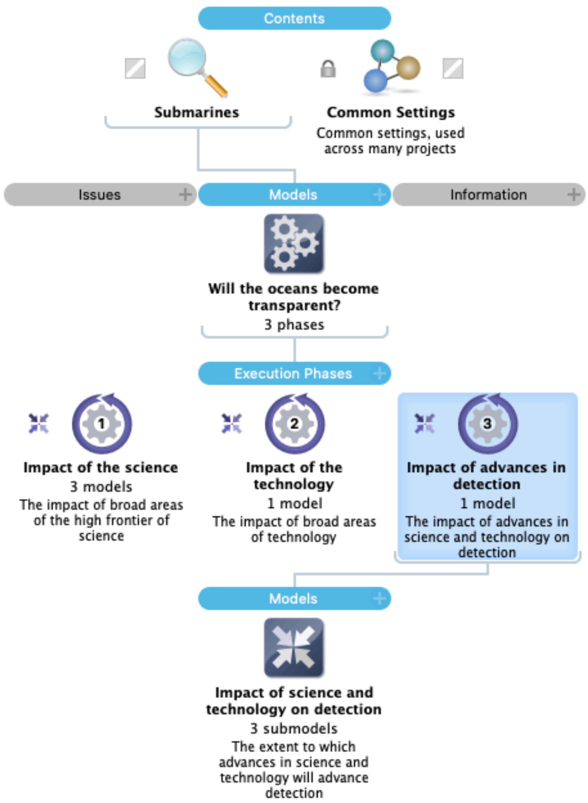
2.1 Execution phases of the model



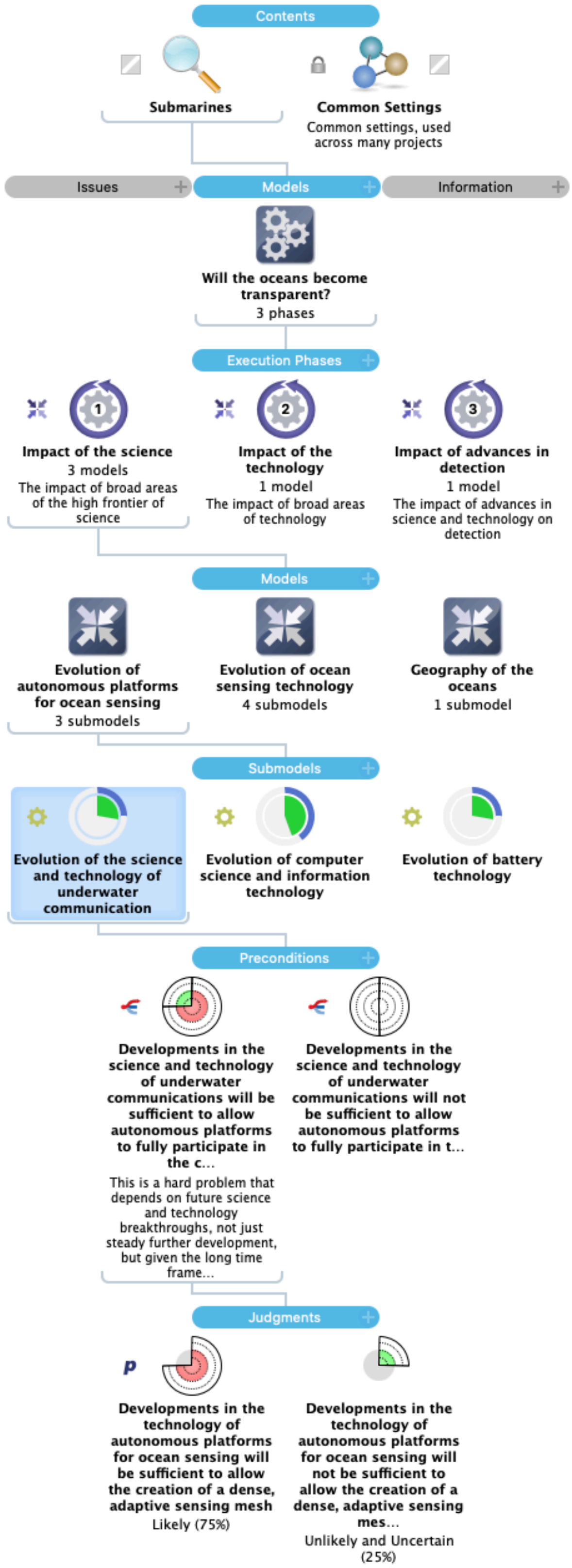
2.2 First execution phase



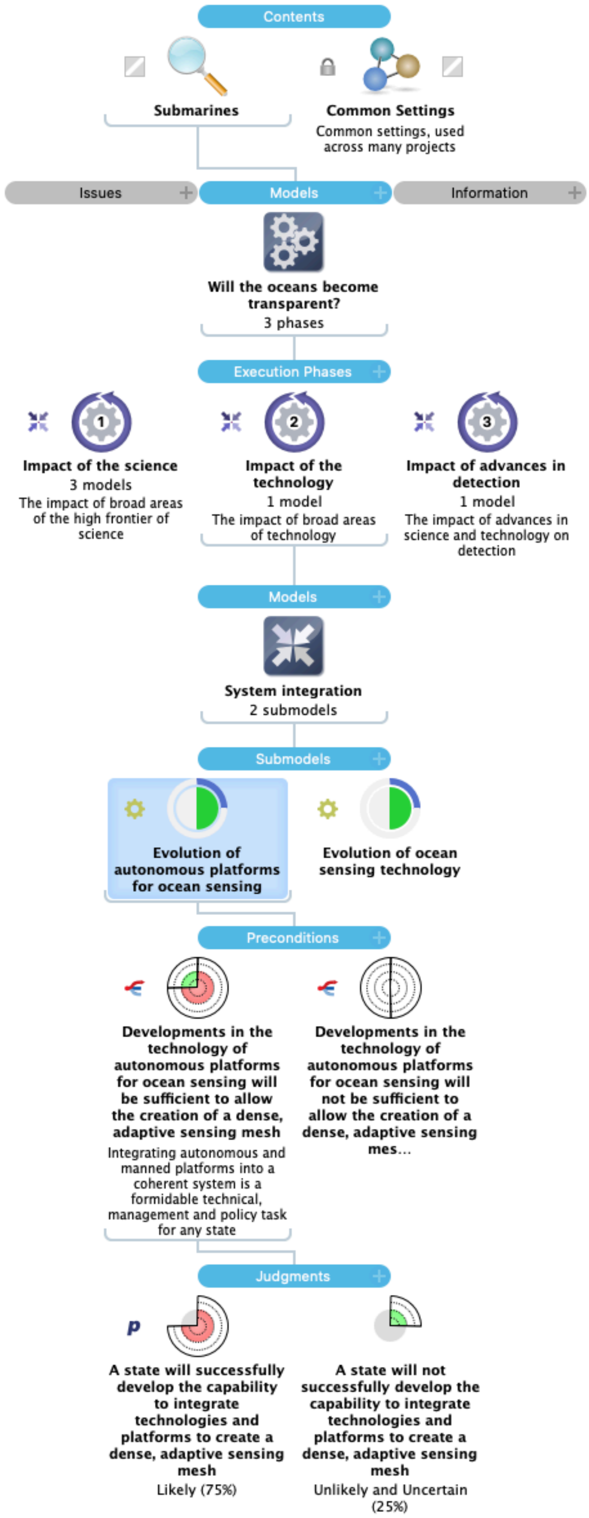
2.3 Second execution phase



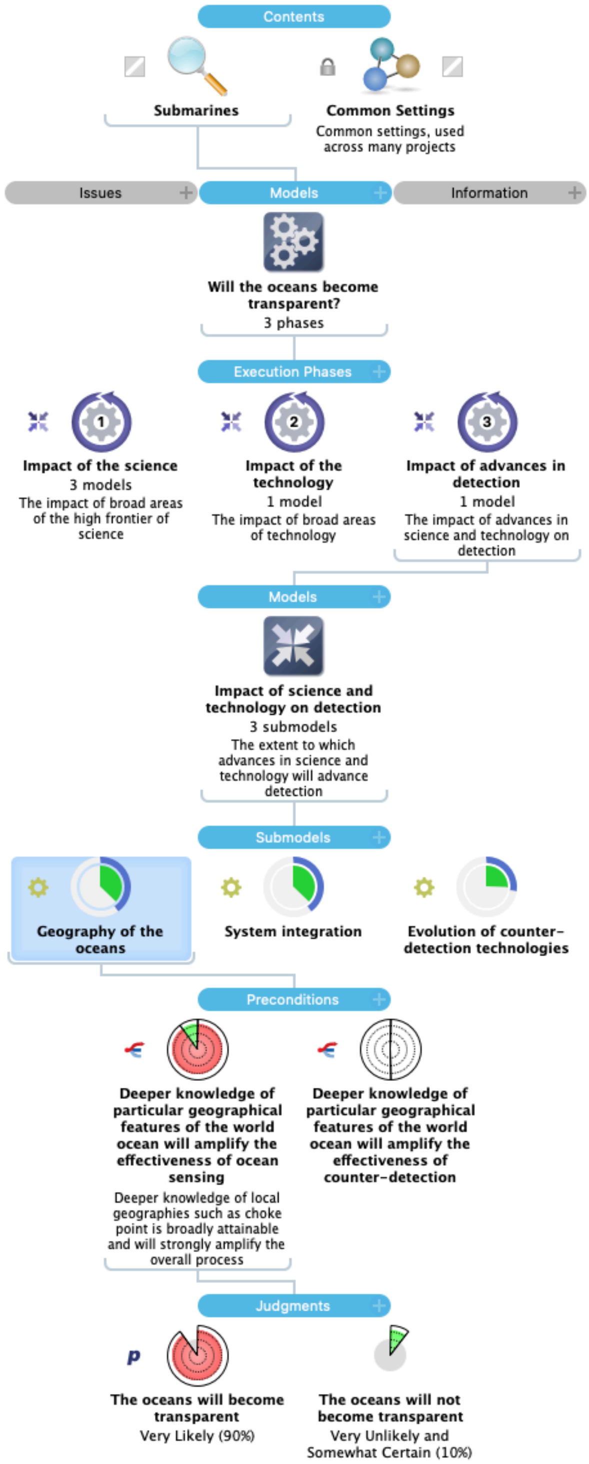
2.4 Third execution phase



2.5 Expansion of a submodel in first phase



2.6 Expansion of a submodel in second phase

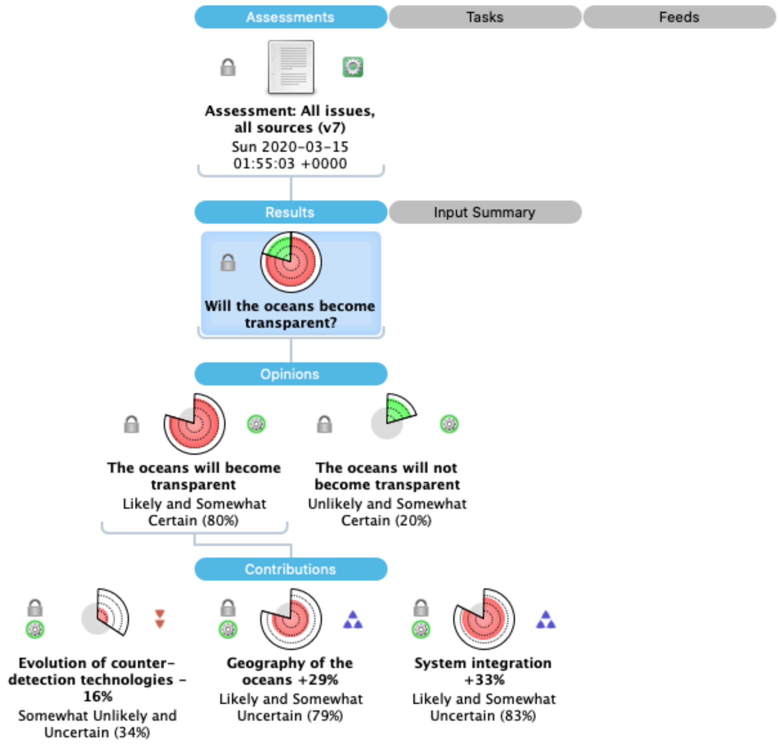


2.7 Expansion of a submodel in third phase

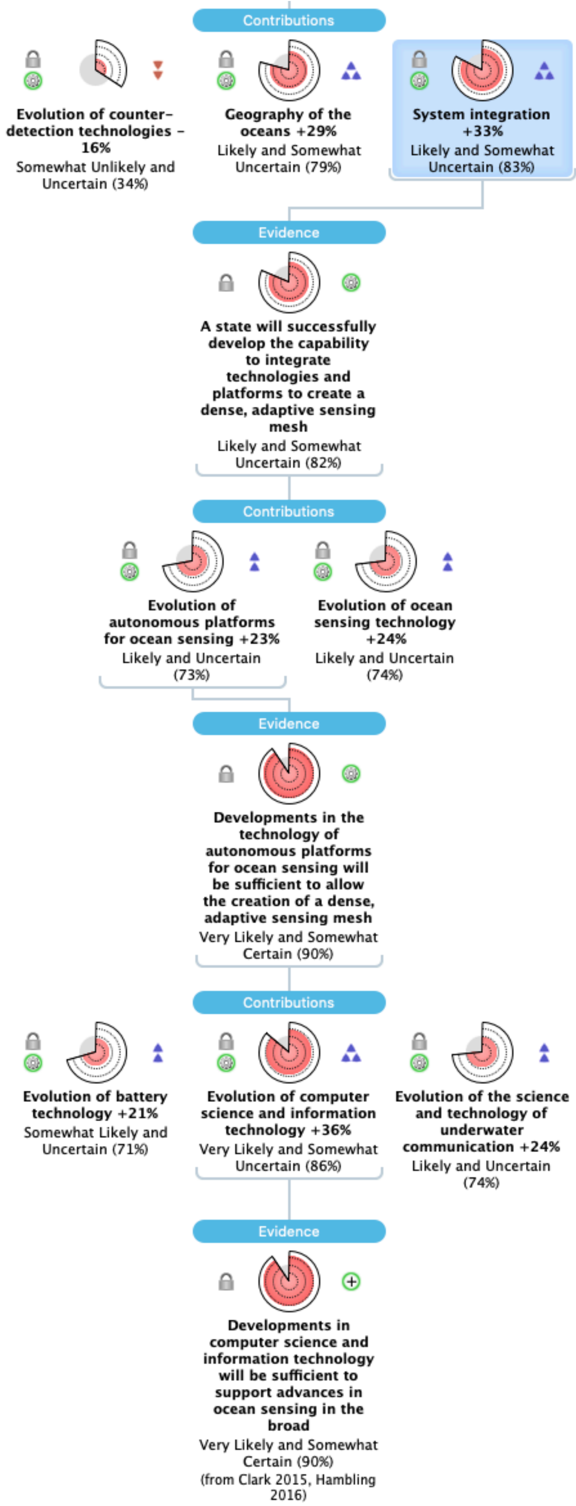
Appendix 3

Assessment Results

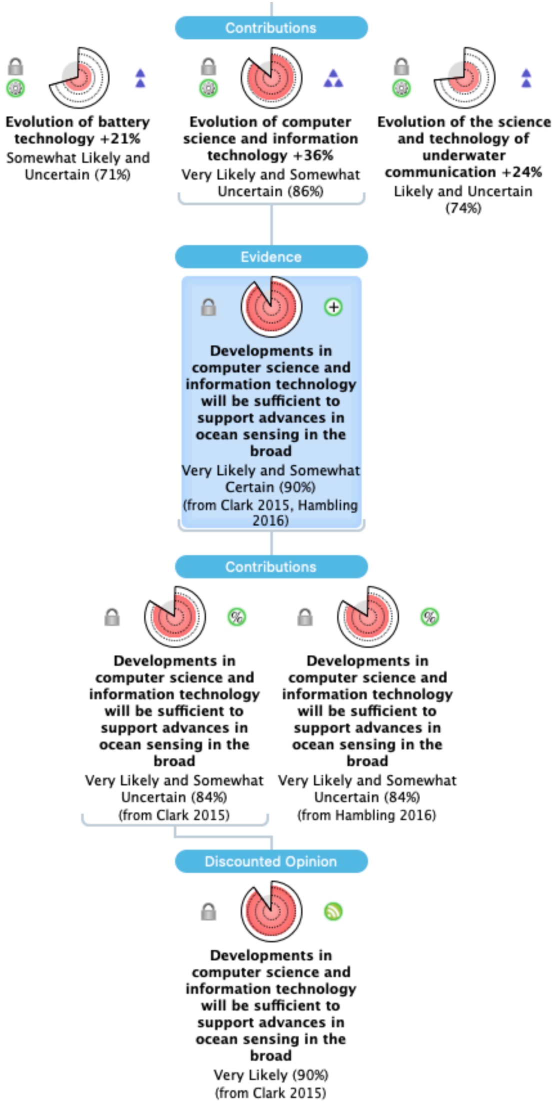
Some screen shots of the main assessment results as organised in the *Intelfuze* system are shown below.



3.1 Top level contributions to assessment



3.2 Partial expansion of one top level contribution



3.3 Final expansion of one limb

The National Security College (NSC) is a specialist graduate studies school at The Australian National University (ANU) providing academic programs, professional courses, research, dialogue and ideas to improve the quality of national security policy and practice. It is a joint initiative of the Commonwealth Government and the ANU and bridges academia, government and business to develop a new generation of strategic thinkers.

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