Applying holistic thinking to the problem of determining the future availability of technology

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Abstract. Used by NASA and DOD, the Technology Readiness Level (TRL) has been found to contain a number of deficiencies which reduce its fitness for purpose. This paper examines the undesirable situation that created the TRL from the traditional and holistic problem-solving processes. The contribution of this paper to the problem-solving body of knowledge is that the holistic thinking approach could have produced a more useful conceptual tool than the TRL for determining the future availability of technology; a tool that instead of focusing on the early stages of the technology lifecycle focuses on the whole technology lifecycle from conceptualization to obsolescence.

Index terms: TRL, TAWOO, systems thinking, holistic thinking, problem-solving, DMSMS, obsolescence.

I. INTRODUCTION

This paper demonstrates the benefits of going beyond systems thinking and using a holistic thinking problem-solving approach using the TRL [2] as an example. The paper shows how instead of producing the TRL which focuses on the early stages of the technology lifecycle, an alternate approach to the problem came up with a different solution that covered the whole technology lifecycle. Section II frames the problem based on the extended problem-solving process which begins with an undesirable situation [3]. Section III describes the traditional problem-solving approach which produced the TRL as the solution to determining the maturity of a particular technology as well as discussing some defects in the TRL. Section IV illustrates the holistic problem-solving approach which rephrases the problem statement altering the scope of the problem in a significant way. It leads the project manager into considering:

1. The rate of change of technology maturity during its development.
2. The wider issues pertaining to the obsolescence of the technology once in service.

Section V discusses the holistic thinking process that combines perceptions from the *Temporal* and *Generic* perspectives to suggest the Technology Availability Window of Opportunity (TAWOO) as an alternative conceptual solution to the problem of estimating technology maturity. Moreover, the conceptual TAWOO extends the TRL beyond the early stages of technology development and considers the issues from entire the technology use or lifecycle perspective and includes consideration of Diminishing Manufacturing Sources and Material Shortages (DMSMS) at the end of the technology lifecycle. Since the TAWOO is a concept, Section VI provides pointers towards further research. Lastly, Section VII contains some of the benefits of the holistic approach in this context.

II. FRAMING THE PROBLEM

This section frames the original problem as providing "*a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology"* [2] in the context of the following problem-formulation framework [4]:

- ***An undesirable situation:*** the lack of "*a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology*"[5].
- ***A Feasible Conceptual Future Desirable Situation (FCFDS):*** a situation that contains a "*systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology"* [5].
- ***The problem:*** how to transition between the undesirable situation and the FCFDS, namely first to conceptualize and then to develop a "*systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology"*.
- ***The solution:*** the product that will operate in the FCFDS to provide the remedy to the undesirable situation.

III. THE TRADITIONAL APPROACH

This section discusses the traditional approach employed in the 1990's which produced the TRL to provide a baseline reference.

A. *The undesirable situation*

The undesirable situation is articulated in a focused manner as follows:

- It is 1998.
- A system under development is to be deployed in 1999 to meet a projected need.
- There is no current suitable technology that can be employed for realizing that system.
- There is no systemic and systematic way to determine the readiness of a technology for use in a product other than seeing it incorporated in current products [5].

B. *The FCFDS*

The technology is ready in 1999 when needed and in used in a fully operational deployed product or system.

C. *The problem*

Create a tool or a methodology (or both), that a project manager can use to determine if a technology is mature enough to integrate into the system under development so that the FCFDS will be created in a timely manner.

D. *The solution*

The solution in 1998 was the TRL shown in Table 1; a tool that was developed in NASA to provide a "*systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology*" [2]. The

Table 1 NASA's TRLs

9	Actual system "flight proven" through successful mission operations
8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
7	System prototype demonstration in a space environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

project manager could assess various technologies and determine which one to use. TRLs = 1, 2, 3, and 4 seem to constitute the research levels, TRL = 5 and 6, the development levels and TRL = 9, the production level. The TRL was used in NASA and later adopted by the US Department of Defense (DOD) [1] to assess a technology and approve it for use if it was above a certain TRL.

Whilst the TRL seems to be well-known, a number of deficiencies in the TRL which reduce its fitness for purpose have been pointed out. For example:

- Katz et al. wrote "*Program managers underestimate the time and technical effort needed to mature technologies above TRL = 6 to achieve higher levels of maturity*" [6].
- Sauser et al. wrote [7] "*it has been stated that the TRL:*

does not provide a complete representation of the (difficulty of) integration of the subject technology or subsystems into an operational system [8-11],

includes no guidance into the uncertainty that may be expected in moving through the maturation of TRL [8, 9, 12-15], and

assimilates no comparative analysis technique for alternative TRLs [8, 9, 11, 12, 14]".

Sauser et al.'s Point 2 which aggregates findings [8, 9, 12-15] is very pertinent since the TRL is a single data point. While single data points provide information on current status of a something they cannot, and should not, be used to predict the future. No wonder "*Program managers underestimate the time and technical effort needed to mature technologies above TRL = 6 to achieve higher levels of maturity*" [6]. This situation has been recognised and there has been research into historical data and project success and failure to develop ways of reducing the uncertainty in the prediction. However, research into the problem of determining future technology readiness such as seeking ways to reduce the uncertainty in the predictions [16] still remains focused on the early stages of the technology lifecycle [17].

IV. THE HOLISTIC THINKING APPROACH TO REMEDYING THE UNDESIRABLE SITUATION

Systems thinking provides an understanding of the structure of the system, the operational relationships between the system and adjacent systems and the functional relationships between the components of the system [18]. Holistic thinking goes beyond systems thinking to provide

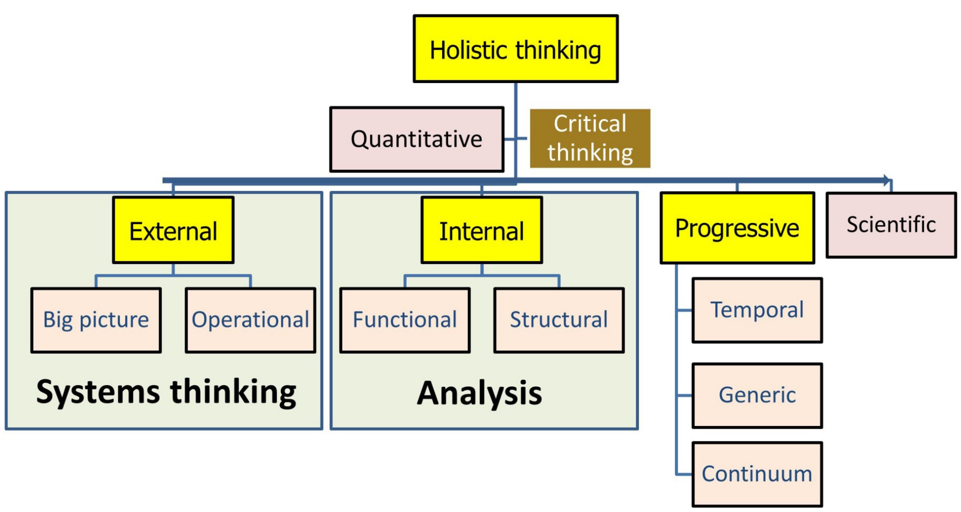

Figure 1 The Holistic Thinking Perspectives (Structural perspective)

solutions using that understanding and an understanding of the similarities and differences between the situation at hand and other situations to identify problems and conceptualize and provide solutions [4]. The holistic thinking approach:

1. Is an iterative process of inquiry [19].
2. Goes beyond Gharajedaghi's four perspectives [19].
3. Is based on Richmond's seven streams of systems thinking [20].
4. Perceives an undesirable situation from nine external, internal, progressive and other Holistic Thinking Perspectives (HTP) shown in Figure 1.
5. Couples the HTPs with active brainstorming [4] to allow the problem-solver to think in a systemic and systematic manner about a system (ideation).
6. Incorporates critical thinking (ideation and idea evaluation).
7. Recognizes that each descriptive HTP provides a partial view of the situation.

The descriptive external perspectives are:

1. ***Big Picture:*** the context for the system.
2. ***Operational:*** what the system does: a black box perspective.

The descriptive internal perspectives are:

3. ***Functional:*** what the system does and how it does it: a white box perspective.
4. ***Structural:*** how it is constructed and organized.

The progressive perspectives are where holistic thinking goes beyond analysis and systems thinking. The descriptive progressive perspectives are:

5. ***Generic***: where the system is perceived as an instance of a class of similar systems.
6. ***Continuum:*** where the system is perceived as but one of many alternatives.
7. ***Temporal:*** which considers perceptions of the past, present and future of the system.

The remaining other perspectives are:

8. ***Quantitative:*** a descriptive perspective of the numeric and other quantitative information associated with the system.
9. ***Scientific:*** a prescriptive perspective; the hypothesis or guess about the issue, cause and solution.

A. *The undesirable situation*

The undesirable situation is the same as in Section III.A. The holistic approach perceives the specific instance of the undesirable situation from each HTP as discussed in this section.

IV.A.1. *Big Picture perspective*

The same perceptions from the *Big Picture* perspective are articulated as in Section III.A. In addition, other *Big Picture* perceptions include:

- Any other assumptions about the technology.
- A description about need of technology for the product (system).
- A description of environment in which product incorporating the technology will be used.
- A list and description of the known users of the product.
- A description of the adjacent systems interfacing with the product.

IV.A.2. *Operational perspective*

Perceptions from the *Operational* perspective include scenarios of the different types of missions the product using the technology will perform. Typical generic scenarios include the use of the product incorporating the technology in different categories of missions such as:

- One-of-a-kind, single use, short- and long-term missions such as the NASA planetary space explorers in the 20th Century. NASA generally developed the technology for a spacecraft for a mission. Since the number of spacecraft were small, the technology could be used at TRL = 6. A small number of spacecraft could be crafted and deployed without being placed in mass production.
- One-of-a-kind military targets of opportunity such as Operation Chastise, May 16th, 1943 which went operational at TRL = 6. The special purpose dam-busting bombs were crafted and deployed for that specific mission without being placed in mass production and made available for other types of missions.
- Examples of various uses of the technology in considerable numbers of commercial and military products over a long period of time. This type of deployment requires TRL = 9 to guarantee availability of the technology when needed.
- Various in-between scenarios

IV.A.3. *Functional perspective*

Perceptions from the *Functional* perspective describe how the technology functions.

IV.A.4. *Structural perspective*

Perceptions from the *Structural* perspective include limitations of the technology imposed by its physical structure.

IV.A.5. *Quantitative perspective*

Perceptions from the *Quantitative* perspective indicate:

1. The maturity of the technology can be represented in monotonically increasing levels of technology ranging from a ‘concept that needs to be developed’ to ‘being incorporated in significant quantities of production items’. The GAO relates TRL to programmatic risk as shown in Figure 2 [1].

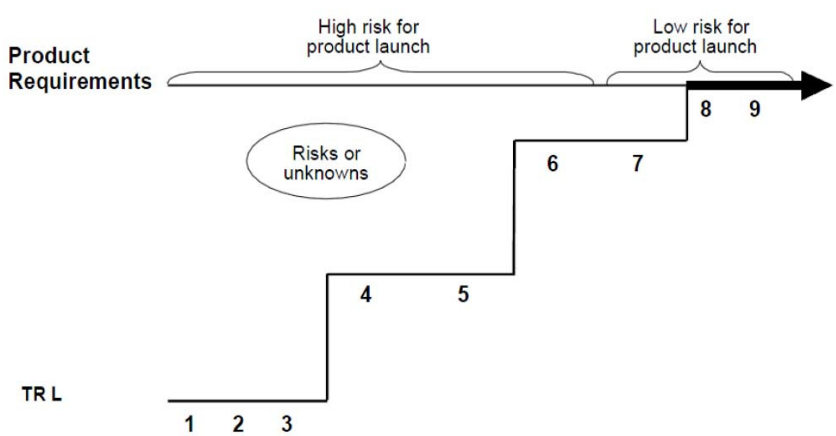

Figure 2 Programmatic risk as a function of TRL[1]

2. Nine levels of technical maturity shown in Table 1 comply with Miller's rule of 7±2 [21] for comprehension of an issue.

IV.A.6. *Generic perspective*

Perceptions from the *Generic* perspective include ways of assessing readiness and capability to do something, including:

- Capability maturity models.
- Competency models.
- ISO 9001.
- Risk assessment rectangles.
- Temperature thermometers or other meters with useable range markings.
- The 'S' curve which illustrates the introduction, growth and maturation of innovations and technology.

IV.A.7. *Continuum perspective*

Perceptions from the *Continuum* perspective include:

1. The differences in the types of operational uses for the technology mentioned in Section IV.A.2.
2. The different types of missions which are described in the *Operational* perspective.
3. The differences between
    a. using a methodology and a tool to assess the <u>current</u> state of something, and
    b. using a tool to predict the <u>future</u> state of the same thing.
4. Risks and risk management pertaining to the misuse of the methodology and tool.

IV.A.8. *Temporal perspective*

Perceptions from the *Temporal* perspective include:

1. Technology maturity and obsolescence are currently considered independently in the technology use cycle. This is a key observation leading to the inference in the *Scientific* perspective to change the problem from 'technology readiness' to 'technology availability'.
2. The technology use cycle which has been shown in the form of the whale diagram [22].
3. Once ready for use in products, technology is only available during the adulthood and maturity phases of the technology lifecycle.

IV.A.9. *Scientific perspective*

Perceptions from the *Scientific* perspective infer:

1. While a single TRL can provide information on the current maturity level of the technology, it cannot, and should not, be used to predict the maturity level of the technology at a future date.

B. *The FCFDS*

The FCFDS is that the project manager has a tool or methodology to determine if a specific technology will be available when needed for the duration of all categories of missions.

C. *The problem*

The inference from the *Scientific* perspective of the FCFDS is to restate the problem as "to create a tool or methodology (or both) to allow the project manager to determine if the technology will be available when needed for the duration of all categories of missions".

The tool or methodology will need to take into account at least the following:

- Time to advance maturity to a level suitable for use in the project which will depend on category of mission (single, one-of-a-kind, use or mass production).
- The period of time in which the technology is available for use in products and systems before it becomes obsolete.
- Obsolescence issues now considered separately as Diminishing Manufacturing Sources And Material Shortages (DMSMS).

This rephrasing of the problem statement has altered the scope of the problem in a significant way. It leads the project manager into going beyond systems thinking and using the *Temporal* perspective to consider:

1. The rate of change of technology maturity during its development.
2. The wider issues pertaining to the obsolescence of the technology after deployment.

D. *The solution*

In the holistic problem-solving process, at least two solutions (tools and/or methodologies) would be conceptualized and a selection would be made to determine the most acceptable solution. For the purposes of this paper, consider the conceptualization of one of those solutions.

V. THE TECHNOLOGY AVAILABILITY WINDOW OF OPPORTUNITY

The Technology Availability Window of Opportunity (TAWOO) is one conceptual solution to the problem. Going beyond systems thinking, consider the TAWOO from the appropriate progressive and other HTPs.

A. *The Temporal perspective*

According to Crépin et al., "*Although TRL is commonly used, it is not common for agencies and contractors to archive and make available data on the timeline to transition between TRLs*" [16]. The *Temporal* perspective suggests that the data should be archived and used to estimate/predict maturity. If that data were available, one could infer from the *Scientific* perspective one could consider the rate of change of TRL in a manner similar to Figure 2 such as shown in Figure 3.

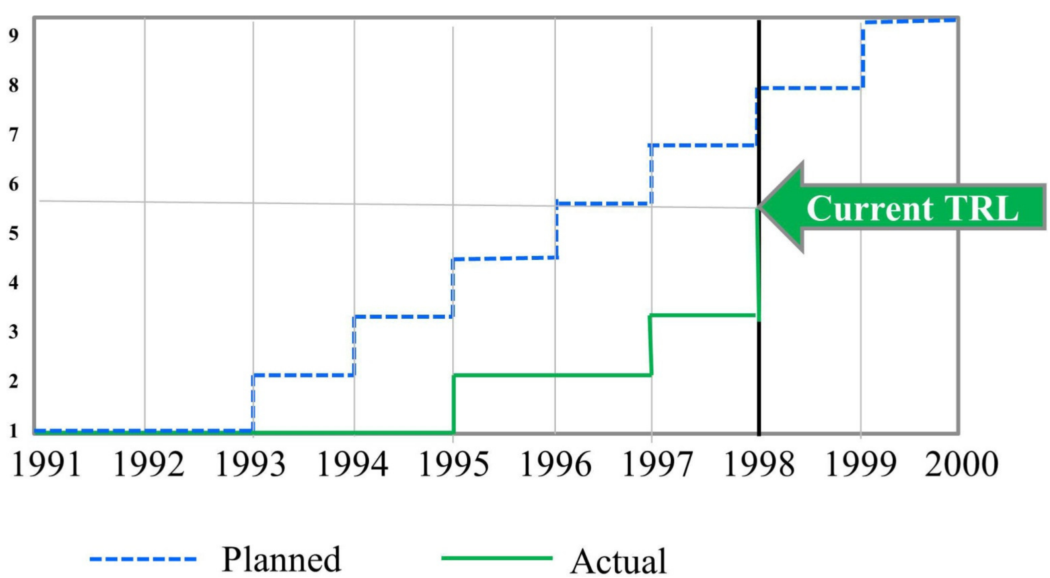

Figure 3 TRL 1991-2001

Figure 3 shows that the technology was conceptualized in 1991 and the development was planned to advance one TRL each year starting in 1993 for production in 1999. However, the development did not go according to plan. The technology did not get to TRL = 2 until 1995 advancing to TRL = 3 two years later in 1997 and jumping to TRL = 6 in 1998. So, can the technology be approved for a project due to go into service in 1999? It depends. If the project can use the technology when TRL = 6, then yes. But, if the product using the technology is to go into mass production, the answer cannot be determined because there is insufficient information to predict when the technology will be at TRL = 9. The project will have to obtain more information about the factors affecting the change in TRL.

B. *The Generic perspective*

Perceptions from the *Generic* perspective indicate that that projects use Earned Value Analysis (EVA) and display budgeted/planned and actual cost information in graphs.

C. *The Scientific perspective*

When the rate of change of TRL is displayed in the form of an EVA graph as shown in Figure 4, one additional significant item of information is obtained. Assuming nothing changes and progress continues at the same rate as in 1997-1998, the technology should reach TRL = 9 by 1999. However, the reason for the rate of change between 1996-1997 and 1997-1998 is unknown. This provides the project manager with some initial questions to ask the technology developers before making the decision to adopt the technology. The static single value TRL has become a dynamic TRL (dTRL) [23]. The dTRL component would make adoption choices simpler. Prospective users of the technology could look at their need by date, the planned date for the technology to achieve TRL = 9 and the past progress through the various TRLs. Then the prospective users could make

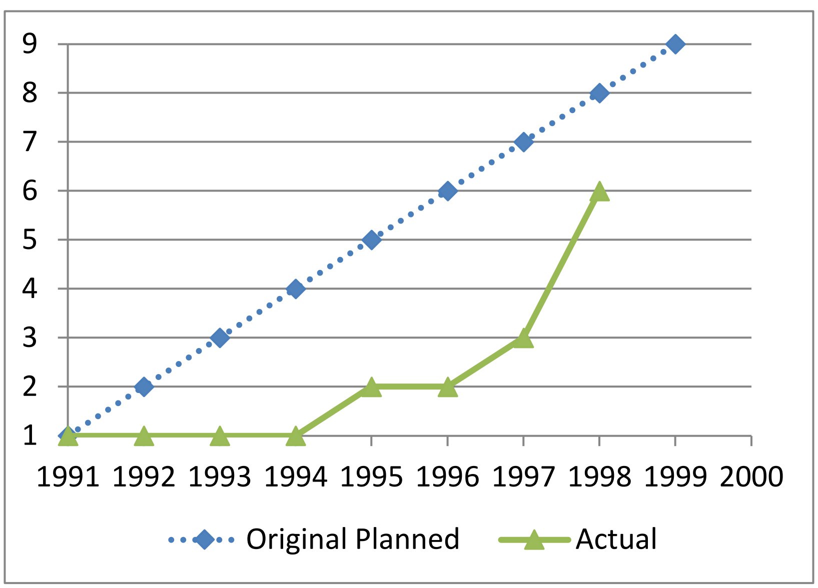

Figure 4 The dynamic TRL (dTRL)

an informed decision based on the graph in their version of Figure 4. If the rate of change projects that the desired TRL will not be achieved when needed and they really needed the technology, they could investigate further and determine if they could help increase the rate of change of TRL.

Table 2 TAWOO Levels

TAWOO State	Level	Comments
Research and Development	1-8	Same as for TRL, **but with a dynamic rate of change component.**
Operational	9	Same as for TRL. Available for use in new products (in general).
Approaching obsolescence	10	Use in existing products but not in new products. Plan for replacement of products using the technology.
Obsolete	11	Some spares available, maintenance is feasible.
Antique	12	Few if any spares available in used equipment market. Phase out products or operate until spares are no longer available.

Insight from the *Temporal* and *Generic* HTPs has conceptualized the use of a dTRL to help to predict when a technology will achieve a certain TRL. The need for a dTRL has been recognized in practice and there has been research into estimating the rate of change of technology maturity [17]. The dTRL concept was used for quite a few years the US aerospace and defense industry beginning in the Strategic Defense Initiative era (early 1990's) and took the form of waterfall charts that tracked the TRL [24].

While the dTRL addresses the front end of the technology lifecycle, the issues pertaining to the other phases of the technology lifecycle may have to be addressed in a different manner. One framework might be the TAWOO levels as shown in Table 2 which extend the TRL through the whole technology lifecycle. However, should the dynamic aspect of levels 1-8 be overlooked, the TAWOO will become just as useless as the TRL.

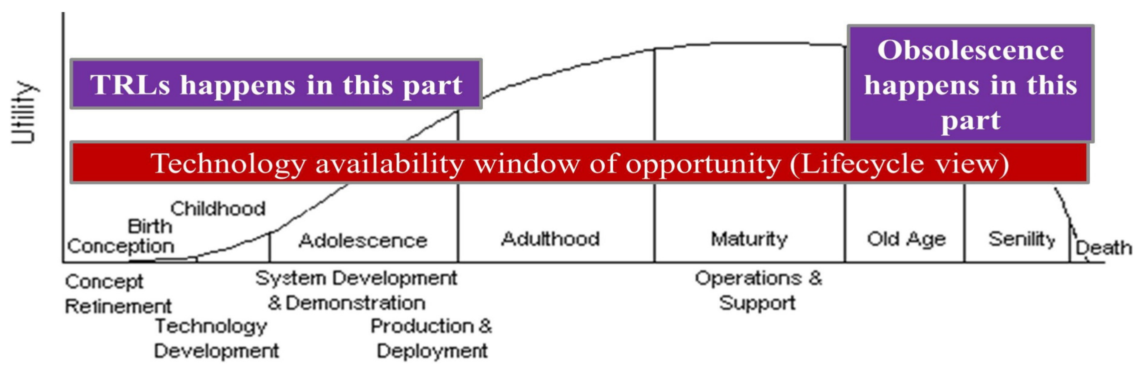

Figure 5 TAWOO superimposed on the Whale diagram

VI. DIRECTIONS FOR FUTURE RESEARCH

As far as future research into the problem of determining technology availability is concerned, the conceptual TAWOO provides one solution to the problem of conceptualizing a tool for predicting the availability of technology for use in a product in circumstances when the technology needs time to mature from its current state to an appropriate level. If the TAWOO is superimposed on the whale diagram [22] as shown in Figure 5. The TAWOO also provides information about the availability of the technology in the remaining stages of the technology lifecycle. Further research needs to be done on the concept to determine its feasibility and to produce a useable tool. For example:

- Are there alternatives to the TAWOO?

- How to reduce the uncertainty in the prediction estimates.
- Is it possible to develop a generic TAWOO template for different types of technology?
- What form would the information display take; tabular, line graph, pie chart, bar charts, traffic light, whale chart, etc.?
- Reviewing the literature on DMSMS to determine the ways of predicting when obsolescence will occur and how should that information be displayed in the TAWOO?
- Would comparing ways of estimating the dTRL and future obsolescence be useful?
- Is the ‘S’ curve (innovation domain) useful?

VII. BENEFITS OF HOLISTIC THINKING

This paper has provided an example of applying holistic thinking to the problem of determining the availability of a technology for use in a system and illustrated a number of improvements over the traditional approach as follows:

1. The holistic approach redraws the boundary of the problem posing different questions to those posed by the traditional approach. For example:
   a. The traditional question “what is the maturity of the technology?” produced the TRL.
   b. Using the framework in Section II the question changed to “when will the technology be <u>ready</u> for use?” and produced the dTRL.
   c. The resulting holistic approach question “when will the technology be <u>available</u> for use?” produced the TAWOO which might predict when the technology will be ready as well as the length of time it would be available.
2. Questions b and c were posed as the result of a change of perspective.
3. The whole lifecycle solution came from a combination of the *Generic* and *Tempora*l perspectives, namely a result of going beyond systems thinking

The benefit of the holistic thinking approach in system analysis has also been shown in the case of the Royal Air Force (RAF) Battle of Britain Air Defence System that was used to foil the Luftwaffe’s attempt to gain control of the sky over southern England in 1940 [4] pages 168-174). There the use of the HTPs identified two preventable failure modes in the system which unfortunately were only identified after the fact.

VIII. SUMMARY

This paper demonstrated some of the benefits of a holistic thinking problem-solving approach using the TRL as an example. Section II framed the problem based on the extended problem-solving process which begins with an undesirable situation. Section III described a traditional problem-solving approach which produced the TRL as the solution to determining the maturity of a particular technology. Section IV illustrated the holistic problem-solving approach which rephrased the problem statement altering the scope of the problem in a significant way. It led the project manager into considering:

1. The rate of change of technology maturity during its development.
2. The wider issues pertaining to the obsolescence of the technology once in service.

Section V discussed the thought process that combined perceptions from the *Temporal* and *Generic* perspectives to suggest the TAWOO as one conceptual alternative solution to the problem. The TAWOO considers the issues from the technology lifecycle perspective and includes consideration of DMSMS. Since the TAWOO is a concept, Section VI provided pointers towards further research. Lastly, Section VII contained some of the benefits of the holistic approach in this context.

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