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ON CHARACTERIZATION OF TECHNOLOGY READINESS LEVEL COEFFICIENTS FOR DESIGN

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Abstract

Technology innovation is an important driving factor in creating competitive advantage in industries that have evolved by convergence of technology and design. In this industries, technology management is a pillar of design management. One valuable source in technology management is Technology Readiness Level (TRL), initially developed for NASA. The application of TRL numbers has been expanded to estimate the cost and risk of acquisition or development of different technologies. However TRL numbers are ordinal and applying mathematical operations on them create incorrect results. TRL cardinal coefficients are developed to eradicate this error. In this paper TRL cardinal coefficient values for seven NASA aeronautic technologies have been calculated based on Analytic Hierarchy Process. For the first time, the cardinal coefficients are calculated based on a quantifiable criterion. The variable progress in cardinal coefficients indicated a realistic reflection of the nature of the technology development. In addition, cardinal coefficient numbers were mathematically meaningful when comparing the maturity of technology development across different technologies.

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1 INTRODUCTION

In recent years, companies such as Apple, Nokia and Philips have created competitive advantage through their innovative and bold designs. One important element of their innovation in design is the technology that these products carry or introduce to the market. Their technology management is an important element of a design management. Technology as a source of innovation has been the focus of many management studies. One valuable resource in technology management is Technology Readiness Level (TRL). TRL has been developed by NASA to gauge the development of different space technologies (Mankins, 1995). Table 1 shows NASA's most up-to-date TRL documentation that is publicly available in their system engineering handbook (NASA, 2007). TRL consists of nine stages, benchmarking the development of a technology from basic scientific principle up to an actual system proved through successful mission operation.

The detailed definitions of TRL, with descriptions of terminologies such as system, test environment, hardware, and risk, are published by Air Force Research Laboratory for national fixed wing vehicle program (Moorhouse, 2002). Although the definitions were suggested for a specific project, they are applicable to any project in science and technology division. To help project managers in applying TRL as a decision making tool, Moorhouse (2002) gave an appropriate risk level to each TRL, however the risk level definitions were qualitative and nonspecific. Starting in the early nineties, the TRL system was adopted by several industrial sectors. Its application was mostly to manage and monitor the risk of acquisition of technologies in different stages of development (Yasseri, 2013; European Association of Research and Technology Organisations, 2014; Rybicka et al., 2016).

Table 1. NASA TRL values and corresponding definitions (Mankins, 1995)

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

However, the adaptation of the TRL in different industries encountered challenges in terms of its integration and connectivity, scope of TRL assessment, product road mapping, and imprecision of the scales (Olechowski et al., 2015). One major effort has been to extract quantitative information regarding risk level at different stages of technology development (Dubos et al., 2008; Magnaye et al., 2010). For instance Lee and Thomas (2003) estimated a cost-weighted TRL (WTRL) by multiplying the TRL of each component by its percent cost (cost of a component divided by the cost of the whole system) for 28 NASA space programs. They correlated the calculated WTRL with the schedule slippage, which correlated poorly with the coefficient of determination (R^2) equal to 0.26. The poor correlation can be attributed to application of TRL ordinal numbers in calculating WTRL.

In these studies, TRL numbers have been used in mathematical calculations. However TRL numbers are ordinal. It means that they are basically holding a position for a stage of technology development. This means the TRL numbers can be replaced by alphabetical letters with no loss of information regarding the stage of technological development. For instance, although it is clear that TRL 8 is more mature than TRL 2, the ratio of maturity is unknown and probably is not equal to 4. Using ordinal TRL numbers have proven to result in incorrect cost and risk evaluations, and huge cost overruns in the acquisition of technologies (United States General Accounting Office (GAO) Report, 1999). For instance, GAO stated in July 1999 that the solar array for the BS 702 spacecraft was at TRL-6 when launched, and based on calculations using TRL ordinal numbers, zero cost growth and schedule slippage existed. However, following satellite launches in late 1999, 2000, and 2001, the solar array design experienced problems associated with reduced on orbit power and insurance claims were filed for the six spacecraft totalling $1.04 billion (Conrow, 2009).

For the first time, Conrow (2009) developed cardinal coefficients for TRL values to eradicate errors in calculating WTRL. He established a comparison matrix, based on maturity level ratios between TRLs. The maturity ratios were stated to be based on experts' opinion. He calculated the cardinal coefficients, by applying the Analytical Hierarchy Process (AHP) on a comparison matrix. The result of his analysis was a matrix consisting of 9 coefficients (between 0-1) correlating to each TRL value. These cardinal numbers could be compared scale-wise and can be used to calculate the TRL weighted risk or cost. However, in his study, it wasn't clear what formed the basis for converting qualitative experts' opinions to quantitative numbers, or what criterion was used as a yardstick for maturity. The AHP method is as precise as the pairwise comparison that is done between different TRL numbers, therefore, it is advantageous to use a measurable quantity such as development time as a basis for the comparison matrix. In addition, Conrow calculated the cardinal coefficients for an unknown technology project and proposed a regression analysis based on plotting cardinal coefficients vs. their corresponding TRL values, assuming that cardinal coefficients were equal for any technology development project. The validity of this assumption has not been extensively studied.

TRL cardinal coefficients are valuable since they provide a basis for quantitative evaluation of a technology's development. This quantitative basis can be used to compare different technologies, or even same technology at different stages of TRL, and understand the trend of the technology's development. In addition, cardinal coefficients provide a correct mathematical basis to calculate TRL weighted risk or cost for each stage of TRL In this paper, AHP is used to calculate the cardinal coefficients of seven specific NASA's aeronautic technologies (Peisen et al., 1999) and for the first time a quantitative value is used to form the comparison matrix. The criterion for the comparison matrix was the time that it took for each TRL to be developed from the start of the project. This is called maturity time in this paper. The maturity time data was extracted from a public report published by NASA (Peisen et al., 1999). In this study, Conrow's method has been expanded to seven specific aeronautic technologies in order to evaluate the difference between TRL cardinal coefficients across multiple technologies if such a difference exists.

In following sections of the paper, the analytical method for calculating cardinal coefficients is explained in detail; TRL cardinal coefficients for seven NASA's aeronautic technologies from TRL1 to TRL6 (development to prototype testing in relevant environment) are then calculated. Technologies are compared quantitatively in terms of their progression along different TRLs and concluding remarks about the application of cardinal coefficients are discussed.

2 ANALYTICAL METHOD

Analytical Hierarchy Process (AHP) (Saaty, 1990) is used to estimate the TRL cardinal coefficients for seven NASA's aeronautic technologies. AHP is a method of Multi-criteria Decision Making (MDCM) that has been developed by Thomas L. Saaty, mathematician and operation research theorist at University of Pittsburgh (1990). In AHP framework there are defined levels of hierarchy with a goal or an objective that needs to be satisfied on the highest level. Mid- Levels of hierarchy are the criteria that the decision makings are based upon. At the bottom level of hierarchy, alternatives are located. The alternatives need to be compared based on the mid-level criteria to satisfy the highest level objective. By organizing the problem in hierarchical manner, the complex relationship between objectives, criteria, and alternatives can be clarified.

In AHP, the comparison between different alternatives is done by scaling the desired criteria. As discussed in the introduction, comparing ordinal TRL numbers is not accurate mathematically. In this paper, maturity time has been used as a criterion for pairwise comparison between TRL values. The maturity time is the length of the time taken for each project to progress to a certain level of TRL.

Table 2 shows the time required for seven NASA technologies to make transition from one TRL to the next TRL up to TRL6.

Table 2. Time required for 7 NASA Technologies to make transition from one TRL to the Next TRL, up to TRL 6 (Peisen et al., 1999)

Name of the technology		**Carbon-6 Thermal Barrier**	**Fibre Preform Seal**	**Non-destructive Evaluation**	**Tailless Fighter**	**Thrust Vectoring Nozzle**	**Low Emission Combustion**	**Direct To**
Years								
From TRL	To TRL							
1	2	0.4	1	0.5	3	0.3	1	0.2
2	3	0.4	1.5	1	1	0.3	1	0.1
3	4	0.4	1.5	1	1	0.4	1	0.1
4	5	0.5	1.5	1	1	2	2	1.1
5	6	0.2	6	1	2	2	4	0.1

The pairwise comparison was done by calculating the ratios of maturity time for each TRL. There are 6 TRLs (in this case study), therefore for each TRL number, there will be 6 set of pairwise comparisons to 6 other TRL values (including itself). The result of pairwise comparison for TRL 1 to TRL 6 will be a 6×6 matrix, consists of ratios of TRL maturity times. The pairwise comparison matrix A can be expressed as Equation 1 and the expanded version of matrix A for this case study is shown in Equation 2:

$$A = a_{ij} \qquad where \qquad i,j = 1,\dots,6 \tag{1}$$

$$A = \begin{bmatrix} {}^{t_{TRL1}}/_{t_{TRL1}} & {}^{t_{TRL1}}/_{t_{TRL2}} & \cdots & {}^{t_{TRL1}}/_{t_{TRL6}} \\ {}^{t_{TRL2}}/_{t_{TRL1}} & {}^{t_{TRL2}}/_{t_{TRL2}} & \cdots & {}^{t_{TRL2}}/_{t_{TRL6}} \\ \vdots & \vdots & & \vdots \\ {}^{t_{TRL6}}/_{t_{TRL1}} & {}^{t_{TRL6}}/_{t_{TRL2}} & \cdots & {}^{t_{TRL6}}/_{t_{TRL6}} \end{bmatrix} \tag{2}$$

where t_{TRL1} is the maturity time for a TRL1. A sample detailed calculation of comparison matrix A is shown in Appendix A.

By looking through the Table 1, it is clear that there is no maturity time for TRL1. In reality this might be true, since TRL1 is related to a stage that a scientific principle is observed. The principle might have been established for a long time as a result of a different research and development project. This causes TRL1 to be an unknown value in comparison matrix. One logical assumption is that it is zero. However, this assumption creates infinite numbers for the first column of comparison matrix. Another choice could be an equal, non-zero value for all the technologies. This will eliminate the effect of TRL1 across all the projects. In this paper, it is assumed that TRL1 for all the projects is equal to 1 year. This assumption might create inconsistency in comparison matrix calculation which will be examined at the end of this section.

The diagonal of matrix A is equal to 1.00, because the maturity of each TRL to its own is equal to 1. Another characteristic of matrix A is that it satisfies the reciprocal condition which means:

$$a_{ij} = \frac{1}{a_{ji}} \tag{3}$$

These two major characteristics of matrix A are aligned with Saaty's AHP comparison matrix (1999). The next step is to calculate the TRL cardinal coefficients based on the comparison matrix. The cardinal coefficient of the matrix A is equal to its eigenvector (υ).

$$A.\upsilon = \lambda.\upsilon \tag{4}$$

where υ is the eigenvector of matrix A and is a 6×1 matrix as shown in Equation 5 and λ is the Eigenvalue of matrix A.

$$\nu = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \vdots \\ \nu_6 \end{bmatrix} \tag{5}$$

Since A is reciprocal and positive, the calculation of its eigenvector is equal to sum of its normalized rows. Each element of eigenvector (υ) is the cardinal TRL cardinal coefficients (ν_n) can be calculated using Equation 6:

(6)

$$\nu_n = \frac{1}{6}\sum_{j=1}^{6} \frac{a_{nj}}{\sum_{i=1}^{6} a_{in})} \qquad (6)$$

Equation 6 is valid if matrix A is consistent, and A is consistent if and only if Equation 7 is true.

$$\frac{a_{ik}}{a_{ij}} = a_{ij} \qquad i, j, k = 1, \dots, n \tag{7}$$

where n is 6 for the comparison matrix in this case study. The derived eigenvector has a characteristic that the sum of all its values are equal to one. The sufficient condition for A to be consistent is if its maximum eigenvalue (λ_{max}) is equal to its order (n) (Saaty, 1999). However, the comparison matrix A is based on scaling human decisions and some inconsistency may arise from scaling a qualitative human decision to a quantitative number. The Consistency Index (CI) for the comparison matrix can be calculated using Equation 8.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{8}$$

Saaty suggested allowing for some inconsistency, in order to avoid forcing the consistency condition on qualitative scaling. He suggested the ratio of consistency index of comparison matrix to consistency index of a randomly generated reciprocal matrix of the same order to be less than 10% (Equation 9), and he called this ratio, Consistency Ratio (CR) (Saaty, 1999).

$$CR = \frac{CI}{RI} < 10\% \tag{9}$$

where RI is the consistency index for a randomly generated reciprocal matrix of the same order of comparison matrix. For the comparison matrix A that is constructed in this case study and is based on the ratio of the maturity time for each TRL, the only inconsistency source might be the assumption that TRL1 =1. The effect of this assumption on the consistency index for matrix A will be evaluated in the results and discussion section.

3 RESULTS AND DISCUSSION

The pairwise comparison matrices for seven NASA's aeronautic technologies from TRL1 up to TRL6 (when the prototype demonstrated and tested in relevant environment) is constructed based on AHP method. The ratios of maturity time between TRLs were used to calculate the comparison matrix for each technology. The time for development of TRL 1 was assumed to be one year. To examine the consistency of comparison matrices, the consistency index for all the technologies are calculated based on Equation 8. The average consistency index for a sample size of 500 randomly generated 6×6 matrices was 1.24 (Donegan and Dodd, 1991). The consistency ratio is calculated using Equation 9 and results for the seven technologies are tabulated in Table 3. The maximum consistency ratio is 4.03 % for "Direct To" technology and the average consistency ratio is 0.93 across all seven projects. The average consistency ratio is less than a tenth of the threshold of 10% that has been suggested by Saaty (1999). This clearly shows the assumption for calculating TRL1 =1 did not introduce major inconsistencies in the comparison matrices. AHP simplified analysis can be used to calculate the TRL cardinal coefficients for all seven technologies listed in Table 2.

Table 3. Consistency index and Consistency Ratio for TRL cardinal Coefficients

	Consistency Index	Consistency Ratio (%)
Carbon-6 Thermal Barrier	0.63×10-2	0.5
Fibre Preform Seal	0.19×10-3	0.15
Non-destructive Evaluation	0.16×10-3	0.12
Tailless Fighter	0.13×10-1	1.048
Thrust Vectoring Nozzle	0.29×10-3	0.023
Low Emission Combustion	0.11×10-1	0.88
Direct To	0.50×10-1	4.03

TRL cardinal coefficients are calculated based on Equation 6 and tabulated in Table 4. It can be inferred from Table 4 that cardinal coefficients for different technologies are not the same, unlike their corresponding TRL values. The differences between cardinal coefficients can be related to the difference in the type of the technology. Based on Peisen's report (Peisen et al., 1999) the aeronautical technologies are categorized to four different types, namely Airframe, Flight systems, Ground systems and Propulsion. As these technologies matured over time from TRL1 to TRL6, cardinal coefficients increased as well, indicating the increase in maturity of the technology. However, unlike TRL values that increase one step at a time for all technologies, the corresponding cardinal coefficients progressed at different pace, reflecting the actual maturity time ratios. The difference between each cardinal coefficient within a technology implied how the technology developed over time. For instance for “Carbon 6 Thermal barrier” technology, one could conclude that the maturity time for TRL 6 is twice that of TRL 2 (0.24/0.12 = 2). This means the time for development of “Carbon 6 Thermal barrier” from TRL 5 to TRL 6 is double the time for the technology to be developed from TRL 1 to TRL 2. However, by looking at TRL values, this information is unavailable.

Table 4. TRL cardinal Coefficients for seven NASA’s aeronautic projects

	Carbon-6 Thermal Barrier	Fibre Preform Seal	Non-destructive Evaluation	Tailless Fighter	Thrust Vectoring Nozzle	Low Emission Combustion	Direct To
1	0.09	0.03	0.05	0.03	0.06	0.04	0.12
2	0.12	0.07	0.08	0.14	0.08	0.08	0.12
3	0.15	0.11	0.14	0.16	0.10	0.11	0.13
4	0.18	0.16	0.19	0.19	0.13	0.15	0.14
5	0.22	0.21	0.24	0.22	0.25	0.24	0.24
6	0.24	0.41	0.3	0.27	0.38	0.38	0.25

In order the compare the progression of technologies for different projects, the calculated cardinal coefficients vs. TRL numbers for four different sample technologies are plotted in Figure 1.

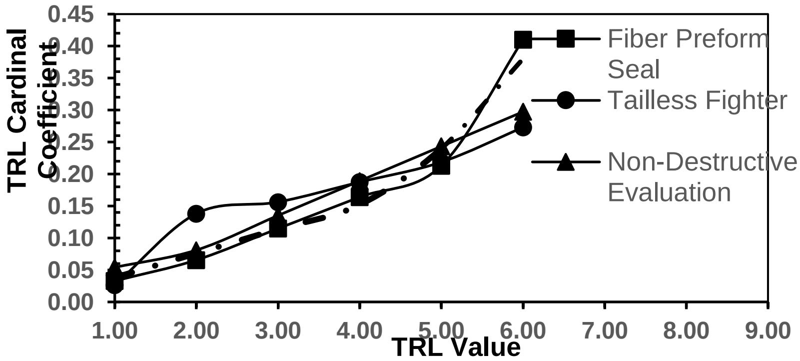

Figure 1. TRL cardinal Coefficients vs. TRL values for three different technologies

As inferred from Figure 1, “Non-destructive Evolution” technology which was categorized as Airframe structure (Peisen et al., 1999) showed a uniform development time from TRL 1 to 6, meaning each stage of the project had the same maturity time to the next level. While “Fiber Preform Seal” Technology which was categorized as Propulsion structure (Peisen et al., 1999) initially progressed fast, after TRL4, the technology took much more time to develop to TRL 6, as is clear from the sharp increase in the slope of the graph from TRL 4 to TRL6. “Tailless Fighter” technology as a Flight system (Peisen et al., 1999) had a non-uniform development as well. The technology development started slow, but after TRL2, it sped up to TRL4, and then slowed down again. TRL cardinal coefficients data indicates that the maturity of technologies over time varies based on the nature of the technology for the studied seven aeronautic projects. This information is not available by using TRL numbers since they show a uniform step wise increase in maturity of the technology for all seven technologies.
Cardinal coefficients of "Low Emission Combustors" and "Fiber Preform Seal" had similar progression at different TRL numbers (Figure 1). Cardinal coefficient vs. TRL values for both technologies had a linear trend up to TRL 5, while the slope of progression increased at TRL 6. Further investigation in Peison's Report (Peisen et al., 1999) indicates that "Low Emission Combustors" and "Fiber Preform Seal" technologies are both Propulsion structures. In addition, the primary focus of both technology developments were performance and both technologies were tested by NASA.

4 CONCLUSIONS

Risk and cost of a development of a technology to a certain TRL level - that is suitable for introducing a product to the market - is an important element of a design process, and needs to be evaluated and examined correctly. Applying mathematical operations on ordinal numbers of TRL creates incorrect estimations of the cost and risk of technology development as part of a design. To eradicate this error, cardinal coefficients have been introduced in the literature. In this paper, AHP is used to calculate the TRL cardinal coefficients for seven NASA aeronautic technologies from TRL1 to TRL6. The maturity time for each TRL is used to construct the pairwise comparison matrix. The selection of time as a specific quantifiable criterion created a consistent basis for comparing the maturity between different levels of the technologies or across different technologies. The resultant TRL cardinal coefficients provided more insight about the nature of progression of technologies over time. Unlike the TRL, which showed a uniform step by step increase in technology development, cardinal coefficients reflected the actual progression of the technology over time.
The calculated cardinal coefficients in this study are based on a quantifiable criterion, therefore, the application of mathematical operations such as comparison or probability functions will result in mathematically accurate and meaningful numbers. Maturity time in this study is an example of quantifiable criteria to form a basis for comparison between technology development based on their TRL cardinal coefficients, however application of AHP as a multicomponent decision making tool will allow the expansion of the single variant criterion that was used in this study to multiple variants such as cost and risk level, providing multidimensional information regarding the technology development.

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APPENDIX A

The comparison matrix A for a sample technology, "Carbon- 6 Thermal Barrier", based on Equation 2 is calculated. A sample calculation for the second column of matrix A, using maturity time data in Table 1 is calculated and shown in Equation A.1.

$$[a_{i2}] = \begin{bmatrix} t_{TRL1}/t_{TRL2} \\ t_{TRL2}/t_{TRL2} \\ t_{TRL3}/t_{TRL2} \\ t_{TRL4}/t_{TRL2} \\ t_{TRL5}/t_{TRL2} \\ t_{TRL6}/t_{TRL2} \end{bmatrix} = \begin{bmatrix} \frac{1}{(1+0.4)} \\ \frac{(1+0.4)}{(1+0.4)} \\ \frac{(1+0.4+0.4)}{(1+0.4)} \\ \frac{(1+0.4+0.4+0.4)}{(1+0.4)} \\ \frac{(1+0.4+0.4+0.4+0.5)}{(1+0.4)} \\ \frac{(1+0.4+0.4+0.4+0.5+0.2)}{(1+0.4)} \end{bmatrix} = \begin{bmatrix} 0.71 \\ 1 \\ 1.29 \\ 1.57 \\ 1.93 \\ 2.07 \end{bmatrix} \tag{A.1}$$

The 6×6 pairwise comparison matrix for "Carbon- 6 Thermal Barrier" is calculated similar to Equation A.1 and the data is shown in Table A.1.

Table A.1. Pairwise comparison matrix (A) for "Carbon- 6 Thermal Barrier"

TRL/TRL	1	2	3	4	5	6
1	1.00	0.71	0.56	0.45	0.37	0.34
2	1.40	1.00	0.78	0.64	0.52	0.48
3	1.80	1.29	1.00	0.82	0.67	0.62
4	2.20	1.57	1.22	1.00	0.81	0.76
5	2.70	1.93	1.50	1.23	1.00	0.93
6	2.90	2.07	1.61	1.32	1.07	1.00