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Technology Readiness Level Assignment to Industrial Plant System Life Cycle

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Abstract : During the industrial plant system life cycle, required technologies are developed and assessed to analyze their performance, risks and costs. The assessment is called technology readiness assessment (TRA) and the measure of readiness is called technology readiness level (TRL). The TRL consists of 9 levels and through the TRL assessment, the technology to be developed and its components are assigned to their appropriate TRL. TRL assessment should be performed in each life cycle stages to monitor the technology readiness and analyze the potential risks and costs. However, even though the concept of TRL has been largely adopted by numerous organizations and industry, direct and clear assignment of target TRL for each life cycle stage has been overlooked. Direct mapping/assignment of target TRL for each life cycle has benefits as follow: (1) the technical risks condition of each life cycle stage can be better understood, (2) cost incurred if the technology development is failed can be analyzed in each life cycle stage, and (3) more effective decision making because the technology readiness achievement for each life cycle stages is agreed beforehand. In this paper, we propose a steel-making plant system life cycle and TRL assignment to each of the system life cycle stage. By directly assigning target TRL for each life cycle stages, we look forward to a more coordinated (in terms of exit criteria) and highly effective (in terms of technical risks identification and eventually prevent project failure) technology development and assessment processes.

Key Words : Technology readiness level (TRL), steel-making plant life cycle, steel-making plant TRL, TRL assessment methods.

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1. Introduction

1.1 TRL definition by NASA

Technology readiness level is a measurement (scale) of technology maturity to represent the technology's readiness/preparedness to be realized/produced. It is used to clear the ambiguity of the technology development status, that is, instead of reporting that the technology is partly/at some degree ready to be developed/realized, we can mention that the technology has reach level 3 of the technology readiness level. The term technology readiness level (TRL) is introduced by the United States National Aeronautics and Space Administration (NASA) in 1980s which consists of 7 levels, and in 1990s it is revised to 9 levels, as shown in Table 1 [1, 2].

<Table 1> NASA's TRL definition

TRL	Level name	Level description*
TRL 1	Basic principles observed and reported	This is the lowest "level" of technology maturation, where scientific research begins to be translated into applied research and development.
TRL 2	Technology concept and/or application formulated	Once basic physical principles are observed, practical applications of those characteristics can be 'invented' or identified.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept	Active research and development (R&D) is initiated, that includes both analytical studies and laboratory-based studies to constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2.
TRL 4	Component and/or breadboard validation in laboratory environment	Basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard.
TRL 5	Component and/or breadboard validation in relevant environment	Basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications can be tested in a 'simulated' or somewhat realistic environment.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	A representative model or prototype system or system should be tested in a relevant environment, in which several-to-many new technologies might be integrated into the demonstration.
TRL 7	System prototype demonstration in a space environment	Require an actual system prototype demonstration in a space environment, in which the prototype should be near or at the scale of the planned operational system and the demonstration must take place in space.
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	This level is the end of true 'system development' for most technology elements.
TRL 9	Actual system "flight proven" through successful mission operations	This level is the end of last 'bug fixing' aspects of true 'system development'.

*See [2] for complete description and examples.

1.2 TRL definition by other institutions

The 9-level TRL concept becomes widely adapted technology maturity measurement by various organizations, for example: the United States Department of Defense (DoD) [3], United States Department of Energy (DoE) [4], and European Space Agency (ESA) [5]. Also, the International Organization for Standardization (ISO) is creating a standardization on TRL definition and assessment for space systems [6]. Most of the organizations and industries have very similar concept and description of TRLs as of NASA's. The similarities of the TRL definition between NASA and other organizations are compared by the authors and shown in Table 2. We can infer that: (1) other organizations highly refer to NASA's TRL definition, and (2) NASA's TRL definition is highly representative and reliable.

Taking different approach from the organizations/ research institutes, some industries tailored the description and number of levels of TRL to suit their internal enterprise-centered technology development strategies. For example, the automotive industry and subsea industry create 10-level [7] and 8-level [8] TRL scale, respectively.

In South Korea, TRL concept is relatively recognized in various organizations and research institutes, such as Defense Agency for Technology and Quality (DTaQ) [9], Korea Institute of Energy Technology Evaluation and Planning (KETEP) [10], Electronics and Telecommunications Research Institute (ETRI) [11], and Korea Agency for Infrastructure Technology Advancement (KAIA) [12]. The TRL description in the above mentioned organizations also have similar understanding with NASA's TRL definition.

<Table 2> Comparison of TRL definition between organizations

	Level definition			
TRL	NASA	DoD	DoE	Similarity
TRL 1	Basic principles observed and reported			100%
TRL 2	Technology concept and/or application formulated			100%
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept			100%
TRL 4	Component and/or breadboard validation in laboratory environment		Component and/or system validation in laboratory environment	90%
TRL 5	Component and/or breadboard validation in relevant environment		Laboratory scale, similar system validation in relevant environment	90%
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	System/subsystem model or prototype demonstration in a relevant environment	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	80%
TRL 7	System prototype demonstration in a space environment	System prototype demonstration in an operational environment	Full-scale, similar (prototypical) system demonstrated in relevant environment	80%
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	Actual system completed and qualified through test and demonstration		90%
TRL 9	Actual system "flight proven" through successful mission operations	Actual system proven through successful mission operations	Actual system operated over the full range of expected mission conditions.	80%

However, implementation case of TRL concept in the industrial field in South Korea is hard to find. Thus, it seems that the application of TRL concept in South Korea industry has just started.

1.3 Relation of TRL and life cycle

TRL measurement is performed during technology readiness assessment (TRA) or technology maturity assessment (TMA) activity. TRA/TMA is an essential task/activity during technology design/development process of the system life cycle. Among the industrial plant system, we are particularly interested in the steel-making plant system and we focused this paper's discussion on the steel-making plant. We developed a system life cycle for the steel-making plant and referred to it throughout our study. However, the system life cycle definition, and its detailed reasoning, is another area of study and not included in the scope of this paper. In this paper, we use the steel-making plant life cycle as follows:

1. Feasibility study
2. Concept design and technology development
3. Basic design and technology demonstration
4. Detailed design
5. Procurement, construction and installation
6. Transition
7. Operation and maintenance
8. Decommission and disposal

Even though the TRL concept had been developed and adopted extensively, it belongs to the TRA/TMA task without explicit and clear assignment with respect to the system life cycle. In other words, the target TRL to be achieved at the end of each life cycle stages is not transparent, if it is not definitely assigned at all. Besides being a measurement of technology readiness, TRL is also an important aspect in the technology design and development, as it reflects the technical risk possess by the project. Therefore, in this paper, we propose a direct assignment of target TRL to life cycle stages of steel-making plant system life cycle and to emphasize the target TRL as one of key exit criteria in the technical reviews. The assignment of target TRL directly to the life cycle stages has a number of advantages.

1. The technical risk of developing new technology or integrating additional technology to existing system is clear/easy to understand/analyze on each steel-making plant life cycle stage
2. The cost incurred if the technology to be developed/inserted is failed can be analyzed in each steel-making plant life cycle stage
3. Standardization effort of technology readiness at each industrial plant life cycle stage

2. TRL assignment to Steel-making Plant System Life Cycle

2.1 How to perform TRL assessment

To perform TRL assessment on the technology being researched/developed, we have to know the complete components, or at least the principal components, of the technology (because the physical hierarchy of the system grows through the system life cycle, the complete system hierarchy usually not be available in the early life cycle stages). TRL should be assessed on each of the technology's components, based on the abstraction

level of the current life cycle stage. The essential reference to perform TRL assessment is the physical breakdown structure of the technology being researched/developed.

Let us take an example in the steel-making plant: there is a project to build a new environment-friendly steel-making process. The project starts with feasibility study (FS) stage and we perform the processes associated with FS stage. Eventually, we review the exit criteria of FS stage. By referring to the proposed target TRL and steel-making plant life cycle (presented in Table 4), we notice that the target TRL for FS stage is TRL 4. To perform TRL assignment, we should consider two axes of technology development. The first axis is the design maturity of the system hierarchy. FS stage requires the system context abstraction that consist of the system of interest and external systems. The second axis is technical risk aspect that can be analyzed by the TRL assessment. Thus, the TRL of the technology's components should be assessed based on their recognized technical risk, even though the level of abstraction of the system hierarchy has not reach that components.

In our example of steel-making plant establishment, in the FS stage, the system context would consist of the blast furnace system and its external systems. Even though, at this stage, the system architecture (e.g., subsystems) has not developed yet, the researchers/engineers could indicate the principal technology that will be used in the system of interest (steel-making) to achieve the stakeholder requirements, i.e. environment-friendly. The researchers might propose a new approach of steel-making process by introducing a highly efficient melting furnace. Thus, the technology readiness of the melting furnace and its recognized components should be assessed, settled on the TRL scale for steel-making plant (presented in Table 3), and reviewed whether the TRL achievement satisfy the target TRL as one of FS stage's exit criteria.

<Table 3> TRL definition for steel-making plant

TRL	Level name	Description
TRL 1	Technology principle understanding	Understanding of the basic principle of the technology regarding the material, steel-making processes, and steel-making facilities
TRL 2	Technology application concept identification/ definition	Identification of the method of the technology regarding the material, steel-making processes, and steel-making facilities contribution to the product. In other words, technology concept development and application areas identification
TRL 3	Analytical verification of the technology application concept	Analysis/ experiment on the core function of the identified technology related to the material, steel-making processes, and steel-making facilities. Or concept verification of the technology's characteristics
TRL 4	Components performance verification in the laboratory environment	Verification the components or the required performance (laboratory-wise) of the core function of the identified technology related to the material, steel-making processes, and steel-making facilities in the laboratory environment

<Table 3> TRL definition for steel-making plant (continue)

TRL	Level name	Description
TRL 5	Components performance verification in the environment similar with the operating environment	Verification the required performance (components-wise) of the core function of the identified technology related to the material, steel-making processes, and steel-making facilities in the environment similar with the operating environment
TRL 6	System level performance verification in the environment similar with the operating environment	Demonstration the (equipment-wise) model or prototype performance of the core function of the identified technology related to the material, steel-making processes, and steel-making facilities in the environment similar with the operating environment
TRL 7	Performance demonstration trial in the operating environment	Demonstration the equipment prototype performance of the steel-making equipment in the actual operating environment
TRL8	Demonstration of complete operation preparation of the system in the operating environment	Completion of equipment/system development and operation preparation. Complete technology demonstration in the actual operating environment. The technology demonstration shows that the target production/function of the system has been achieved.
TRL 9	Business operation	Operation of the equipment/system for business purpose (commissioning). The commissioning transition procedures are smooth and successful.

2.2 TRL definition for steel-making plant

The TRL definition for steel-making plant has the same number of levels with that of NASA, i.e. 9 levels. The reason is, the production nature of the steel-making plant and NASA's is similar in the sense of one project has one output (project type in consideration is not the mass-manufacturing kind.). However, we defined the TRL for steel-making plant by considering the technology viewpoints of the steel-making plant. There are four main technology viewpoints of a steel-making plant, they are: (1) the material technology as an end product of steel-making plant, (2) the material process technology, (3)the manufacturing machineries design technology, and (4) the manufacturing process technology. TRL definition of steel-making plant is developed by considering the first three viewpoints, as shown in Table 3.

In comparison with TRL definitions of other industries, the automotive industry has 10 levels of TRL because on the 10th level, it considers mass-distribution of the products across the geographic area. The subsea industry has 0-7 levels, an 8-levels TRL, because it does not separate the testing environment into similar environment (to the operational environment) operational environment (TRL 4 is named "environment tested"). Our prediction of this consideration is because the testing environment should be the subsea, regardless whether it is the target operational environment or not. Therefore, by comparing the nature of the system, we adopt 9-levels TRL.

From the TRL definition for steel-making plant in Table 3, we can collect the methods that can be used to achieve the TRL: analytical experiment (TRL 1-3), modelling and simulation

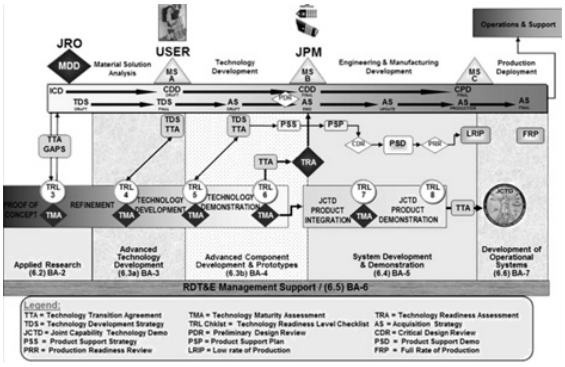
(TRL 4–5), prototyping (TRL 5–6), demonstration (TRL 6–7), commercial verification (TRL 8), and commissioning (TRL 9). One or more of these methods can be performed in parallel with the life cycle processes to reach the desired TRL. Moreover, to decide the achievement of TRL during the exit criteria evaluation of each life cycle stage, every TRL achievement should be supplemented with an outcome/product and a documentation. The proposed outcome/product for every TRL achievement for steel-making plant system life cycle is presented in Table 4.

Although the methods to achieve TRL are relatively well-known in the industrial plant system, including steel-making plant system, the measurement to express the technology readiness, TRL, is not well adapted. Therefore, by adopting the TRL definition presented in Table 3, we can standardized the technology readiness measurement and its relation to the steel-making plant life cycle.

2.3 TRL and life cycle stages mapping

Even though a lot of organizations have defined TRL within their technology development guidelines, they did not consider TRL mapping directly to the life cycle stages as one of the exit criteria. DoD is among the first to attempt to assign target TRL on its life cycle in order to reduce the risk in the technology development [13]. The DoD's risk minimization efforts, including TRL alignment, are shown in Figure 1.

The target TRL mapping to the life cycle stages is highly dependent on the project (system) type. Higher TRL can be assigned for each life cycle stages if a project: (1) has a main mission to develop a novel technology,



[Figure 1] DoD's life cycle and the TRL assignment [13]

(2) has a high risk because the system of interest or the enabling systems implement unverified technology, and (3) involves direct technology development to support the system of interest or enabling system (not bought/ordered from other parties). For DoD's case, most projects have the above mentioned properties, and thus, we could observe the differences between the DoD's and the steel-making plant's TRL assignment.

We propose a mapping/assignment of target TRL to each life cycle stage in the steel-making plant field. By considering the TRL definition (Table 3), the life cycle definition, and the common project characteristics of the steel-making plant, we propose TRL assignment to steel-making plant system life cycle (explained in Chapter 1) as shown in Table 4 (Other TRL and life cycle assignments are possible by exclusively considering the characteristics a certain project).

The life cycle stages of steel-making plant are presented in section 1.3, however, the definitions and goals of the reference steel-making plant life cycle is out of the scope of this paper. Nevertheless, in order to support the reasoning of the target TRL assignment, we explain one of the TRL assignment back-

<Table 4> Target TRL assignment to life cycle stages of steel-making plant system

Life cycle	TRL	Environment	Method	Risk
Feasibility Study	TRL 4	L	M&S	M
Concept design and technology development	TRL 5	S	M&S, Pt	M
Basic design and technology demonstration	TRL 6	S	Pt, Dm	L
Detailed design	TRL 7	O	Dm	L
Procurement, construction and installation	TRL 7	O	Dm	L
Transition	TRL 8	O	CV	L
Operation and maintenance	TRL 9	O	C	L
Decommission and disposal	N/A	N/A	N/A	N/A

Legend:
Environment acronyms = L: Laboratory env., S: Similar with operational env., O: Operational env.
Method acronyms = M&S: Modeling and Simulation, Pt: Prototyping, Dm: Demonstration, CV: Commercial verification, C: Commissioning
Risk acronyms = M: Medium, L: Low

ground as an example. The goal of feasibility study stage is to develop a wide spectrum of ideas and alternatives to support the mission of new project selection. In this stage, a number of technology alternatives are developed and analyzed, and finally one of the technology design is chosen. By referring to the goal of the feasibility study stage, we consider the proposed TRL definition. TRL 1 and TRL 2 deal with technology understanding and its application, which conform to the first part of the goal, i.e. development and analysis of technology alternatives. The second part of the goal, i.e. to choose one technology design, requires verification of the technology function/performance, requires TRL 3. Moreover, in order to reduce the technology risk, especially for new technology development, we felt the need to verify the technology in a laboratory (TRL 4). Thus, the assignment of TRL 4 as the target TRL of feasibility study stage is appropriate.

Target TRL assignment to the life cycle phase is not absolute and can be different depending on the project type, technology risk, application domain, organization, etc. For comparison, TRL assignment for steel-making plant is different from the one of DoD's. For instance, the concept design and technology development phase of steel-making plant requires TRL 5, while the technology development phase of DoD (equivalent with feasibility study) requires TRL 6. One of the reasons is that the next phase of DoD's life cycle is Engineering and Manufacturing Development, thus the technology readiness should be higher in order to be manufactured with low risk; whereas the next phase of steel-making plant life cycle is basic design and followed by detailed design, before the construction takes place, thus lower TRL is acceptable.

3. Tools to perform TRL assessment

3.1 TRL assessment checklist

A straightforward method to assess whether a certain technology component has reach the desired TRL, i.e. TRL assessment, is to list the target TRL requirements and evaluate the component's conditions/statuses against the requirements. The list of requirements is called a checklist. The checklist is filled by the responsible engineers and delivered as one of the materials for technical reviews. The engineers may fill the checklist manually or semi-

automatically by allowing machine learning-supported computer program to remember frequently occurred/matured technology. An example of a checklist to assess the technology readiness as one of the exit criteria of feasibility study stage, that is TRL 4, is shown in Appendix A.

3.2 TRL integration

The TRL of each component of the technology may be different, however, there should be a single representative level of TRL to represent the overall technology readiness of a certain life cycle phase. The overall TRL level is the representative information to be evaluated at the technical review.

We can combine the TRLs of each component to decide the TRL of the technology by selecting the lowest level is the representative level. For example, the components of technology A are component B, component C, and component D. The TRLs of components B, C, and D are TRL 4, 5, and 6, respectively. Then, the TRL of technology A is the lowest achieved TRL of its components, that is, TRL 4. This approach is suitable because the TRL represent the technical risk, thus the lowest level should be highlighted. This approach also adopted by NASA [14].

4. Summary & Future works

In this paper, we proposed an explicit and direct assignment of target TRL to the steel-making plant life cycle, based on the steel-making plant life cycle and TRL definition for steel-making plant. Clear assignment of target TRL to each of the life cycle stage is important because it can analyze and mitigate the technical risk of a project with high degree of technology development. By assessing the TRL in each life cycle phase, we could predict the success or failure of the project and minimize the cost, especially during some of the first life cycle phases.

For future works, we would like to expand this work of TRL assignment to life cycle phases of other industrial plant system. Similar with the efforts done in this paper, we will start with defining the appropriate life cycle and its exit criteria for a certain industrial plant system by considering its project and market characteristics. Then, we will define the TRL for that certain industrial plant and perform the TRL assignment for each life cycle stages. Preferably, we are looking forward to develop a general theory of TRL assignment to the life cycle stage by considering the type of industry, system, project, technology risk, technology maturity, and project/demonstration failure effects on cost, schedule, and performance.

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<Appendix A> TRL 4 Assessment Checklist

No	Exit criteria	Exit criteria description	Yes/No
1	Target technology description	Target technology has been defined	
2	Attributes (characteristics) of the technology	Attributes (characteristics) of the technology have been defines	
3	Measurement for TRL	Technology's (attributes') performance metrics measuring requirements have been established	
4	TRL measurement method	TRL measurement method has been defined	
5	Operational environment	Preliminary definition of operational environment completed	
6	Laboratory environment	Laboratory/test environment is defined based on preliminary operational environment	
7	Laboratory testing requirements	Laboratory testing requirements are derived from system requirements	
8	Experimentation method	Experimentation method has been defined	
9	Experimentation components preparation	Ad hoc and available laboratory components are surrogates for system components	
10	Experimentation target	Experimentation target has been defined	
11	Experimentation target: metrics	System performance metrics and target have been updated	
12	Experimentation target: software	Analysis provides detailed knowledge of specific functions software needs to perform	
13	Experimentation: components	The performance of components has been demonstrated at lab-scale	
14	Experimentation: interfaces	The performance of components and interfaces between components has been demonstrated	
15	Experimentation: multiple components	Subsystems composed of multiple components tested at lab scale using simulator	
16	Experimentation: algorithms	Algorithms converted to pseudocode	
17	Experimentation: supplier	Individual components tested in laboratory/by supplier (contractor's component acceptance testing)	
18	Verification of experimentation results: predictions	Analysis of test results completed verifying performance relative to predictions	
19	Verification of experimentation results: functionality	The technology demonstrates basic functionality in simplified environment	
20	Verification of experimentation results: compatibility	If it is needed, the compatibility of the corresponding components have been demonstrated	
21	Experimentation validation	Cross technology issues (if any) have been fully identified	
22	Experimentation validation: scale-up relationships	Equipment scale-up relationships are understood/accounted for in technology development program.	