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A new approach for compounding system integration risks with system maturity: A supporting methodology in the selection of candidate architectures for a system

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***Abstract*—Integrating a space system is an iterative process aimed at assembling the system according to user requirements and demonstrating through tests that the system is apt to operate in the target environment. The integration effort varies from system to system, and there is no standard methodology for its accomplishment. Researchers have proposed different approaches and metrics to estimate the effort associated with integrating a system. Sauser introduced the concept of an integration readiness level metric (IRL) for a system as a maturity assessment of the integration effort. This methodology parallels the technology readiness level (TRL) introduced by NASA in the 80s to assess the maturity of new technologies in a space system. The authors propose a methodology for the risk assessment of a system's internal interfaces that translates and quantifies the perception of work teams about the challenges involved in the integration of a system. It consists of a structured survey of specialized opinion among project technical personnel to capture relevant technical and programmatic risks related to integrating system elements. The framework is designed to support the processes associated with choosing a system architecture. Although proposed for application in the early phases of the life cycle of a space system project, there are no restrictions on its application to different projects and life cycle stages. Applications include ranking systems components and interfaces according to readiness level and integration risks, supporting risk management in conventional risk management processes and supporting risk-informed decision-making processes to select system architectures.*

I. INTRODUCTION

1.1 Context

Assessing the maturation of both new technologies and their interfaces in a system is critical to the success of advanced development projects. The attendance of performance, schedule and budget requirements are central to project execution.

Between phases 0 and B of the life cycle of a space project, the project team carries out the following tasks: definition of mission requirements, identification of architecture concepts, feasibility analysis, identification of activities and resources, evaluation of initial technical and programmatic risk, elaboration of technical and functional requirements, among others. During these phases, the decisions that commit a large part of the project's resources occur.

Early identification of the risks and uncertainties of these decisions may avoid critical failures affecting performance, schedule, or budget. In the initial phases, thus, managers shall have the necessary technical support for identifying risks and putting in place strategies for minimizing them, mainly the risks that have the potential for adverse developments in performance, cost, and schedule.

A study carried out by Reeves et al. [1] with two National Aeronautics and Space Administration (NASA) projects has shown that among 135 identified risks, most are internal to the project. Many of these risks are usually related to technical activities, including system integration. The study demonstrates the importance of decision-making in a project, mainly in the initial phases.

Risk management methodologies may vary from one organization to another. NASA preconizes the practice of risk-informed decisions in all instances that affect the security, performance, cost, and execution time of a mission[2].

Among the decisions mentioned above, the choice of the system architecture deserves special attention. The option for a given architecture presents long-lasting repercussions in a project and should be carried out within the best available technique and information. The main architecture challenges that have the potential to impact performance, cost, and time must be identified and mapped. Among them, one finds the definition and selection of the architecture's constituent parts and the difficulties posed by their integration.

The integration of a space system is an iterative process, with a significant number of concurrent tasks carried out by a multidisciplinary team, aimed at assembling the system according to user requirements and, at each stage, demonstrating through tests that the system is apt to operate in the target environment. The integration effort may vary from system to system, and there is no standard methodology for its accomplishment.

Researchers have proposed different frameworks and metrics to estimate the maturity of system components and interfaces. In general, such metrics attempt to quantify the integration effort and the maturity of the whole set of interfaces. In this line, Sauser et al. [3] introduced the concept of an integration readiness level metric (IRL) for a system. This methodology parallels the technology readiness level (TRL) metric introduced by NASA in the 80s[4] to assess the maturity of new technologies in a space system.

Researchers have dedicated significant effort to developing methodologies to identify and quantitatively define the risks associated with the evolution of the maturity of the elements of a system. Often, difficulties regarding the technological advancement of system components and interfaces and their subsequent infusion may result in schedule delays, cost overruns, cancellations, or failures[5].The Research and Development Degree of Difficulty (R&D3) metric[6, 4]estimates the probability of failure of an R&D project. Together with the TRL assessment of the project, which in the methodology gets related to the impact of the project's failure, the R&D3 metric provides the necessary input elements for a project's risk management. The Advanced Degree of Difficulty Assessment (AD2) framework [5] extends the above approach. It considers the scenario of the project of a system. It attempts to provide basic information for the project's Technology Development Plan and improve the management of the projects' cost, schedule, and risk [7].

This article explores a methodology for assessing integration risks, which shows similarity to the AD2 framework. It ponders integration maturity indices with risk factors, aiming at translating and quantifying the perception of work teams about the challenges accruing the integration work of a system.

1.2 Problem

Risk identification is commonly undertaken during the early design phases but often fails to identify all events and circumstances that challenge project performance. Risk events associated with the maturation of the technologies considered during the design of a system and those associated with system integration may have significant repercussions on the cost and schedule of the corresponding project. Therefore, it is imperative to (a) identify the maturity level of technologies and interfaces, (b) identify the risks associated with the maturation of the technologies and interfaces that have a maturity level below that defined as a minimum for infusion in the project and (c) identify the risks associated with the integration of the system and its elements. For instance, NASA's projects for space systems require a minimum TRL index of 6 for all technologies and interfaces belonging to a system baseline architecture[8, p. 1].

In project communications, managers should emphasize attributions, interaction, integration, and reliability. Otherwise, significant problems are more likely to occur, especially those linked to interfaces [9].

The problems that this work proposes to address may be summarized as follows:

a) the mismatch between expectations of project managers and work teams about the resources required to deal with the integration of system elements;

b) lack of identification or poor understanding of the risks related to schedule and cost that the decision-maker is accepting when adopting a specific system architecture solution;

c) lack or insufficiency of communication when considering competing alternatives and their associated risks.

1.3 Objective

In this article, the authors propose an interface risk assessment methodology that weighs integration maturity indices with risk factors, with the latter conveying the perception of work teams about the challenges and risks involved in the integration of a system.

The methodology consists of a structured way of capturing a broad spectrum of technical and programmatic risks related to integrating system elements. The proposed risk assessment methodology will, in principle, be capable of addressing the technical and programmatic difficulties foreseen in the integration of a system.

The generated information will aid project managers when comparing different architectural solutions since most of the architecture problems, potentially impacting both cost and time, will, in principle, have been brought to light. The information will also assist managers in design decision-making and purchase decisions, such as selecting sources for acquiring equipment or subsystems.

II. LITERATURE REVIEW

The TRL index measures the maturity of individual system technologies at a given time in a project. Its computation at different phases of a project enables an assessment of the evolution of the work performed throughout the project's phases. In the development and production of flight systems, TRL assessments are usually carried out until the end of Phase B. Afterwards, data from the engineering, qualification, and flight models at different system levels typically provide enough information for assessing the maturity evolution of technologies [10, p. 15].

NASA adopted a seven-level Technology Readiness Level (TRL) metric to assess the development of a particular technology in the 1980s [11].The metric evolved into the current nine levels metric in the 1990s. Since then, the TRL methodology has been widely used at NASA as a systematic metric/measurement system to assess the maturity of a particular technology and enable the ranking of different technologies concerning their maturity[8].

According to the prescription by NASA [12, p. 3], typically, new technology conception takes place from TRL 1 to 3, and development and demonstration from TRL 4 to 6. After reaching TRL 6, new designs would follow the usual engineering development cycle, which involves building and testing engineering and qualification models. After qualification, the system reaches a readiness level for flight with a TRL 8 level assignment. After successful launching and in-orbit operation, the system is finally assigned a TRL 9 level.

The measure provided by the TRL methodology may have different applications: project internal communication; setting of a target/success criterion; project planning; technology selection; communication or establishment of integration arrangements; portfolio management; cost estimation; risk indicator; and guide or measure for engineering development before Preliminary Design Review (PDR)[10]. Fig. 1displays the process currently commended by NASA for TRL assessment at a given project instant. Space projects typically involve a blend of either existing, evolving, or advanced technologies [13].

The TRL of a system technology does not measure the difficulty of integrating this technology into an operational system [13, 14]. TRL is a measure of the maturity of individual technology. The maturity assessment of several technologies integrated into a system is not given by a trivial composition of the individual TRLs. Knowledge of individual TRLs does not provide insight into the components' integration maturity or the resulting system's overall maturity. Yet complex systems have an appreciable chance of failing at integration points [15].

The question of computing the maturity of a system from the maturity of its component technologies, including system-specific characteristics, such as integration maturity, has received significant attention. The proposed frameworks vary in how the TRL of system individual technologies are compounded with measures of system-specific characteristics, such as integration and manufacturing readiness, to produce a whole-system readiness level. NASA preconizes the TRL of a system as being determined by the lowest TRL present in the system [12, p. 26]. The European Cooperation for Space Standardization (ECSS) equally preconizes that "… *a TRL can only be reached by an element if all of the sub-elements are at least at the same level* …"[16, p. 17]. Sauser et al. [8] introduced the concept of System Readiness Level (SRL),which gives the maturity of a system as a composition of the maturity of the system components with the maturity of the interfaces between the components. The latter is given by a matrix, termed integration readiness level (IRL) matrix, having as its elements the maturity assessment of each interface between pairs of technologies. Just as the TRL is used to assess the maturity of developing technologies, the IRL is used to assess the maturity of integrating these technologies. Formally, the SRL is computed as a composition of the IRL and TRL metrics [8, 17, 18]. The IRL scale has evolved over the last decade, with the most recent improvements published by Austin and York [19, 20]. More specific studies aimed at understanding the SRL dependency or sensitivity on a given component technology, in terms of this technology's impact on the readiness, cost, and overall performance of the system, are provided by Gove et al. [21].

There has been a great deal of discussion regarding a proper definition and method of computation of the SRL index of a system, with the publication of several different proposals [22, 23, 24, 25, 26, 27]. In particular, Ross [27] has proposed a framework that differentiates between the technology readiness level of an isolated technology and its maturation status concerning insertion in a given system. The readiness level of a given technology is taken as dependent on the target system's maturity characteristics considered for its insertion, such as its integration maturity. In this framework, the TRL of each component technology is multiplied by indices, with values between zero and one, measuring component promptness for integration and manufacturing. The whole-system maturity readiness level is then taken as the average of the computed maturity levels of the system components.

The TRL assessment at different project milestones gives an overview of technology maturity progression towards a planned application. However, the knowledge of TRL values at varying instants of the life cycle does not provide enough information for assessing technology development risks [10, p. 40].Differences in TRL indices do not measure either the effort or the risk involved in moving from one TRL level to the next in an R&D development [4, 10, p. 40]. Hence, other metrics have been proposed to assess technology risks and effort for progression in a project.

Mankins [6, 4] has proposed the Research and Development Degree of Difficulty (R&D3) metric, which gives a qualitative estimate of the probability of failure for an R&D project with an assignment scheme containing five difficulty levels. The approach proposed by Mankins, termed Technology Readiness and Risk Assessment (TRRA), combines the R&D3 probability with a qualitative estimate of the impact of project failure (F). Using the pair (R&D3, F), a diagram like the probability x impact matrix in risk management is constructed. Risk classification for technology maturation is then implemented, as illustrated in Fig. 2. The impact of project failure is taken as proportional to the difference between the current and target TLR, multiplied by a factor referred to as Technology Need Value (TNV), which gives a measure of the expected impact of a failure in making the considered technology available for future programs. The TRRA framework considers the scenario of a technology project inside an R&D program. The framework must be adapted in several ways when considering the scenario of the project of a system that involves innovative technologies, such as developing and manufacturing a satellite. There is, for instance, the parallel development of different technologies to be integrated into the system, changing TNV assessment definitions.

The Advanced Degree of Difficulty Assessment (AD2) methodology by Bilbro [5] expands theR&D3 scheme by combining the information from several maturity level metrics, such as Integration Readiness Levels, System Readiness Levels, Manufacturing Readiness Levels, and others. In the AD2 methodology, the number of difficulty levels is increased from five to nine, in line with the current TRL scale.

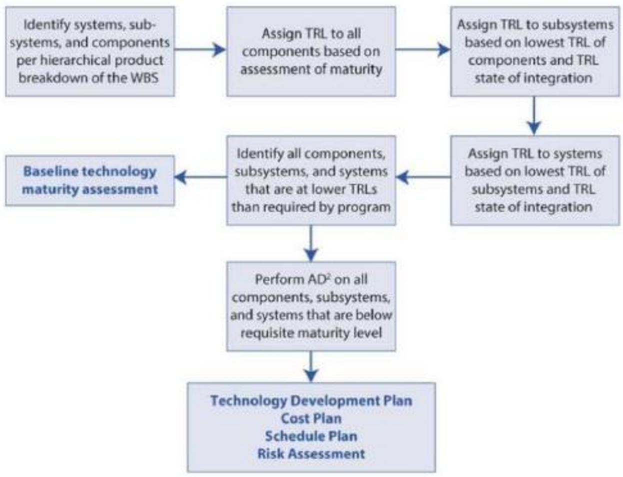


Fig. 1: Recommended NASA technology assessment process [28]

The AD2 framework considers the scenario of developing a system with a broad range of possibilities regarding the component technologies, from new developments to the partial or total reuse of heritage technologies.

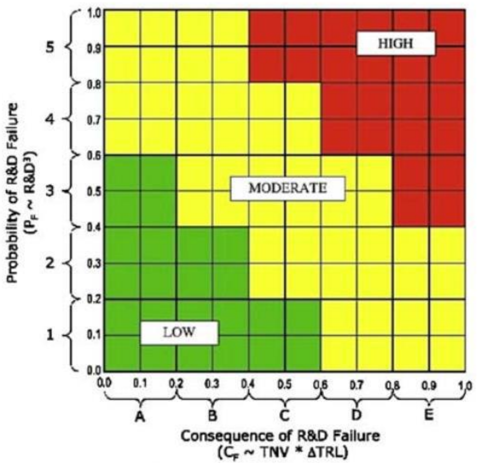


Fig. 2: Mankins [4]. A typical result of the Technology Readiness and Risk Assessment (TRRA) methodology. Each technology is characterized by a point in the diagram. Regions with different colors provide the risk classification for each technology

The system architecture defines the system's physical building blocks in terms of functions and interfaces. The project team chooses the system architecture by the end of Phase A and the beginning of Phase B. Usually, there are two or more paradigmatic proposals. For each proposal, several possible variants spring up from the possibilities opened by, for instance, alternative technologies, make or buy tradeoffs, reuse of equipment or subsystems, alternative subsystem or equipment providers, and so forth. Careful system decomposition and decision-making processes are normal activities at this stage, which precedes the system requirements review (SRR) when subsystems' preliminary design receives full attention. After the SRR, decomposition and decision-making processes are still regular activities, but now at the subsystem level.

To support decision-making processes and control and monitor the project's progress during these phases, engineering managers usually make use of different metrics, which may be used as input both for RIDM processes and the evaluation of the preliminary and critical design efforts. The metric of Technology Readiness Level has been successfully applied within this context in different organizations, mainly to assess the maturity of technologies envisaged for incorporation into a system or subsystem[29, p. 281]. The TRL index gives the readiness or maturity of a single equipment/technology at a given time instant. The index results from an assignment by qualified personnel using a standard TRL scale.

RIDM processes are carried out whenever decisions involve high stakes, complexity, uncertainty, multiple attributes, or diversity of stakeholders [30]. They are conducted with the intervenience of subject experts, technical authorities, stakeholders, and the decision-maker [30].

Risk management methodology may vary from one organization to another. At NASA, risk management is an integral part of the Systems Engineering process[28]. It emphasizes the use of risk analysis in a broad sense, promoting the practice of risk-informed decisions in all instances that affect the security, performance, cost, and execution time of the mission.

The NASA Risk Management Process (RM) integrates two complementary processes in a single framework: Risk-Informed Decision Making and Continuous Risk Management (CRM). The RIDM process addresses the selection of a given alternative among a set of options based on the qualitative and quantitative (probability) assessment of each choice by a qualified panel to ensure the selection process achieves performance objectives. The RIDM process is applicable throughout the project life cycle whenever critical tradeoff decisions, such as architecture and design decisions, make-buy decisions, source selection in significant procurements, and budget reallocation, are demanded [30, p. 13]. The CRM process deals with the selected alternatives' risk management, planning actions to mitigate and control the associated risks, and avoiding performance shortfalls[30, p. 14].

Table. 1 gives a brief description of different studies and corresponding references concerning the concepts of TRL, SRL, and risk associated with technology maturation in a project/program.

Table. 1: Assessment techniques

Study	Description
TRL Schedule Risk Curve	This quantitative model does not communicate the maturity of technology at a certain point in time but instead leverages the TRLs metric to identify the appropriate schedule margins associated with each TRL level to mitigate schedule slips [31].
SRL Max	The SRL Max is a quantitative mathematical model aiming to maximize the SRL under constraint resources. The SRL MAX's objective is to achieve the highest possible SRL based on the availability of resources such as cost and schedule [32].
Advanced Degree of Difficulty (AD2)	Leveraging the concept of RD3, the AD2 augments TRLs by assessing the difficulty of advancing technology from its current level to the desired level on a 9-tier scale [33].

Research And Development Degree of Difficulty (RD3)	The RD3 is a 5-level scale intended to supplement the TRL by conveying the degree of difficulty in proceeding from the current TRL state to the desired level, with five being very difficult and one being the least difficult to mature the technology [6].
Technology Readiness and Risk Assessment(TRRA)	"*TRRA is a quantitative risk model that incorporates TRLs, the degree of difficulty (RD3) of moving a technology from one TRL to another, and Technology Need Value (TNV). The TRRA expands the concept of the risk matrix by integrating*" the "probability of failure" on the y-axis and the "consequence of failure" on the x-axis[34].

III. METHODOLOGY

3.1 Description of the proposed framework

We consider the situation of the project of a space system that incorporates new technologies during the end of Phase A and the beginning of Phase B, when decisions with long-lasting impact are to be taken, such as the definition of the system's architecture. The availability of TRL values at different instants of the project's life cycle does not provide information on the risks associated with technology maturation. It should be supplemented with risk assessments, making use, for instance, of such schemes as the AD2 framework.

The expression "architecture solution" in this article is defined as the set of specific elements (products Part Numbers) that make up the physical architecture. To compare different architecture solutions, we consider that an assessment of integration risks shall complement the TRL data of system components and the IRL data of interfaces; additionally, an evaluation of the technology maturation risks pointed out above should be available. Typically, these data are fed into RIDM processes that substantiate decision-making activities.

Analyses of the work of integrating each interface, considering all candidate equipment, shall focus, for each alternative, on the following points: the type of the integration, i.e., electrical, mechanical, thermal, signal, etc.; the risk of delays in the program; the risk of an increase of the initially estimated cost for the realization of the system; the identification of difficulties and challenges associated with each alternative.

This routine must be applied to the complete system, considering all supply options. In this way, a system integration risk assessment is produced for each architecture solution, giving visibility to the system compositions with the most significant potential for adverse developments regarding the performance of the work of integration, schedule, and cost.

The information gathered will typically make part of the input data package for the tradeoff study to select the most balanced system architecture, possibly within the scope of a RIDM process. Once a choice has been made among the options, the identified risks must be addressed and mitigated, typically in a project's CRM risk management process.

The integration risk assessment shall be carried out for all interfaces of each architecture configuration by specialists involved in the project and performed separately.

The assessment is carried out for a specially selected set of integration risks, chosen according to the experience of one of the authors (HES)in space projects and through interviews with systems engineering teams, specialist engineers, project managers, and Assembly, Integration, and Testing (AIT) teams of the Brazilian space program. They constitute a set of risks that cover most of the causes for cost and schedule increases in space systems development.

Table. 2 lists the selected risks in the format used in the assessment. The questions were designed in the form of an ordinal unipolar survey [35]. Each *general* risk event is unfolded into three excluding possibilities, with the leftmost possibility being taken as the *zero point* option. The *general* and unfolded risk options were carefully chosen to explore project integration risks localized in the relevant severity region highlighted in *Fig. **3***. The three possibilities are associated with different impacts of the corresponding *general* risk. Selection of the first option, referred to as *Negligible (N)*, indicates that the assessor considers that the event associated with the stated *general* risk has a low likelihood or no chance of occurring. Selection of one of the other two possibilities, referred to as *Low (L)* and *Moderate to High* (*M/H*), indicates that the evaluator considers the risk relevant, with severity in the range from low to medium (option 2) or from high to extremal (option 3). The assignment of option 1 to a given risk indicates that the evaluator assesses its likelihood at less than 30%. Table. 3 shows the assumed likelihood levels[7].

Table. 2: Classification criteria of the expected difficulty in integration

	Risk Statement	Unfolded Risk Options: N - Negligible	L - Low	M/H - Moderate to high
Know-how 1	Given that the personnel belonging to the following teams: a) system, (b) manufacturing, and (c) integration might not entirely dominate the technological solutions to be employed in the interface integration, there might be unanticipated technical difficulties, adversely impacting the integration work, therefore leading to interface nonconformities and schedule and cost overruns.	The technological solutions to be employed in the interface integration are thoroughly dominated by the personnel belonging to the following teams: a) system, (b) manufacturing, and (c) integration team.	The technological integration solutions are not thoroughly dominated by the personnel of one of the following teams: a) system, (b) manufacturing, and (c) integration team.	The technological integration solutions are not thoroughly dominated by the personnel of at least two of the following teams: a) system, (b) manufacturing, and (c) integration team.
GSE 2	Given the limited state of knowledge about the use of ground support equipment and tooling in the interface integration effort, there is the possibility of unanticipated technical difficulties, adversely impacting the interface integration work, therefore leading to interface nonconformities and schedule and cost overruns.	There are no envisaged challenges regarding ground support equipment and tooling in the integration effort.	There are anticipated entry-level challenges regarding ground support equipment and tools in the integration effort.	There are anticipated moderate to high-level challenges regarding ground support equipment and tools in the integration effort.
Adaptation & Mastery 3	Given that the integration effort might require physical and/or logical adaptations and that the teams involved might not entirely dominate the technology for the necessary adaptions, there might be unanticipated technical difficulties and additional training, adversely impacting the interface integration work, therefore leading to interface nonconformities and schedule and cost overruns.	Any necessary physical (electrical, mechanical, etc.) or logical adaptations involve technological solutions available and thoroughly mastered by the teams involved in the effort to integrate the studied pair.	Any necessary physical (electrical, mechanical, etc.) or logical adaptations will likely involve technological solutions not entirely available or thoroughly mastered by the teams involved in the effort to integrate the studied pair.	Any necessary physical (electrical, mechanical, etc.) or logical adaptations will highly likely involve technological solutions not either available or dominated by the teams involved in the effort to integrate the studied pair.
Task Volume 4	Given that the workload for the mechanical/electrical/logical integration of the interface elements might not be accurately predicted, there might be unanticipated delays, adversely impacting the allocation of personnel to the integration work, therefore leading to schedule overruns.	The workload foreseen by the teams involved in the mechanical/electrical/logic integration of the interface elements is considered very low.	The workload foreseen by the teams involved in the mechanical/electrical/logic integration of the interface elements is considered low.	The workload foreseen by the teams involved in the mechanical/electrical/logic integration of the interface elements is considered moderate or high.
Training 5	Given the possibility of limited knowledge by the personnel from the evaluator's team about training necessities in the face of the scope of the integration work, there might be unanticipated training necessities, adversely impacting the allocation of personnel to the integration work, therefore leading to schedule and cost overruns.	From the perspective of the evaluator's team, the scope of the integration work is well known, and it is highly unlikely that additional training of the personnel will be necessary.	From the point of view of the evaluator's team, the scope of the integration work is reasonably known, and additional, low-complexity training for the teams involved will be required.	From the point of view of the evaluator's team, the scope of the integration work is not thoroughly known, and additional training of moderate to high complexity for the teams involved will be required.
Nonconformance 6	The history of non-conformities and recurrences associated with the technological solution for the integration of the studied pair might indicate the possibility of difficulties in the interface integration work that will lead to time and cost overruns depending on its level of recurrence.	The history of nonconformities and recurrences does not suggest difficulties in the integration work associated with the interface.	The history of nonconformities and recurrence suggests the possibility of difficulties in the integration work associated with the interface.	The history of nonconformities and recurrence strongly suggests the possibility of difficulties in the integration work associated with the interface.

Interface Requirements 7	Given the limited knowledge about the completeness of the technical requirements set, there is the possibility of the need for additional physical and logical requirements, negatively impacting the integration work, leading to time and cost overruns.	The requirement analyses indicate that it is highly unlikely that additional physical (mechanical, electrical, etc.) or logical requirements will be needed during the integration work.	The requirements analyses indicate a low probability that additional physical (mechanical, electrical, etc.) or logical requirements will be needed during the integration work.	The requirements analysis indicates a moderate to high probability that additional physical (mechanical, electrical, etc.) or logical requirements will be needed during the integration work.
Verification Approach 8	Given the current state of knowledge about the scope of the necessary verification work, there might be unanticipated additional analyses and tests associated with the verification effort, adversely impacting the integration work, therefore leading to schedule and cost overruns.	Considering that the scope of the verification work is well-known, it is highly unlikely that additional analyses and tests associated with the verification effort will be necessary.	Considering that the scope of the verification work is reasonably known, there is a low probability that additional analyses and tests associated with the verification effort will be necessary.	Considering that the scope of the verification work is poorly known, there is a moderate to high probability that additional analyses and tests associated with the verification effort will be necessary.
Complexity 9	Given the current state of knowledge about the complexity of the adopted integration technology, there might be an unanticipated increase in the workload and training necessities, adversely impacting the allocation of personnel to the integration work, therefore leading to technical nonconformities and schedule cost overruns.	Considering that the adopted integration technology shows very low complexity, it is highly unlikely that there will be an unanticipated increase in the workload and training necessities.	Considering that the adopted integration technology shows low complexity, it is likely that there will be an unanticipated increase in the workload and training necessities.	Considering that the adopted integration technology shows moderate to high complexity, it is highly likely that there will be an unanticipated increase in the workload and training necessities.

For example, Table. 4 shows the unfolding of the first general risk listed in the first column in Table. 2 into three event possibilities with different impacts. The leftmost option corresponds to the assessment that the risk has a low likelihood or is not applicable. The other options correspond, by design, to the judgment that the risk is relevant, from likely to near certainty chance and severity in the range highlighted in Fig. 3.

	1 Minimal	2 Minor	3 Moderate	4 Significant	5 Severe
1 - Not likely	1	2	3	4	5
2 - Low likelihood	2	4	6	8	10
3 - Likely	3	6	9	12	15
4 - Highly likely	4	8	12	16	20
5 -Near Certainty	5	10	15	20	25
Risk Rating	Minimal 1 - 2	Low 3 - 9	Medium 10 - 15	High 16 - 20	Extremal 25

Fig. 3: Risk classification used in the proposed framework. The highlighted region of the diagram shows the severity (probability x impact) region of the considered risks in the proposed framework

Table. 3: Likelihood levels

Level	Likelihood	Probability of Occurrence
1	Not likely	~ 10 %
2	Low likelihood	~ 30 %
3	Likely	~ 50 %
4	Highly likely	~ 70 %
5	Near Certainty	~ 90 %

An example of a typical evaluation form is given in Table 5. The line *Frequency* gives the proportion of each option *N*, *L*, and *M/H* in the form. The line *Weighting factors* list the weight values for each option; they shall be conveniently defined for the computation of a *weighted average*, which will be taken as a measure of the *riskiness* of the integration work associated with the concerned interface, as will be discussed ahead.

From the filled forms, important information, which expresses the specialized opinion of the project team responsible for most of the integration work's scope, may be extracted from simple statistics. For each selected risk *m* and interface *q*, by computing overall numbers from all forms *l*, one obtains the fraction of options *0* as given by:

$$y_{mq}^{o} = \frac{1}{N_a} \sum_{l=1}^{N_a} Y_{mql}^{o}, \quad (1)$$

$$o \in \{N, L, M/H\},$$
$$m \in \{1, 2, \dots, 9\},$$
$$q \equiv interface\ identificator,$$

where Y_{mql}^{o} is equal to 1 if the evaluator has chosen option *o*, in the form *l*, for the risk *m*; otherwise Y_{mql}^{o} is equal to 0; N_a is the number of filled forms for the interface *q*.

Table. 4: Possible impacts which may emerge from the first risk listed in Table. 2

RISK STATEMENT: *Given that the personnel belonging to the following teams: a) system, (b) manufacturing, and (c) integration may not fully dominate the technological solutions to be employed in the interface integration, there is the possibility of unanticipated technical difficulties, adversely impacting the integration work, therefore leading to interface nonconformities and schedule and cost overruns.*		
Impact		
Negligible or not applicable	2 - 3 (Minor to Moderate)	4 – 5 (Significant to Severe)
The technological solutions to be employed in the interface integration are thoroughly dominated by all the following teams: a) system, (b) manufacturing, and (c) integration.	The technological solutions to be employed in the interface integration are not thoroughly dominated by one of the following teams: a) system, (b) manufacturing, and (c) integration.	The technological solutions to be employed in the interface integration are not thoroughly dominated by two or more of the following teams: a) system, (b) manufacturing, and (c) integration.

Table. 5: Example of an integration risk evaluation form. The numbered lines are in correspondence with lines in Table. 2. The meaning of the acronyms is as follows: N for Negligible, L for Low, and M/H for Moderate to High

Case study identification:			
Evaluator identification:			
Identification of the interface/integration:			
Equip. A:	Equip. B:		
Criteria	N	L	M/H
1 - Know-how	X		
2 - GSE		X	
3 - Adaptation & Mastery			X
4 - Workload		X	
5 - Training	X		
6 - Nonconformance		X	
7 - Interface Requirements			X
8 - Verification Approach		X	
9 - Complexity	X		
Frequency (%) (100 x)	3/9	4/9	2/9
Weighting factors	W_N	W_L	W_{MH}
Criterion's weight	$3W_N/9$	$4W_L/9$	$2W_{MH}/9$

The expression:

$$I_{mq} = W_N y_{mq}^{N} + W_L y_{mq}^{L} + W_{M/H} y_{mq}^{M/H}, \quad (2)$$

gives an index, with values between W_N and $W_{M/H}$, expressing the severity of each considered risk. For I_{mq} near W_N, the risk is considered negligible or non-existent, while for I_{mq} near $W_{M/H}$, the risk is considered severe. By using these indices, it is possible to rank, for each interface *q*, the risks *m* according to their relevance. In this way, from the assessments carried out by each specialist, one obtains the set of risks that the specialized project team considers most critical in the project's system integration effort. The collection of integration risks ranked according to the index I_{mq} provides an easy and convenient way of communicating integration risks across the whole project hierarchy.

It would also be desirable to consolidate the information through a representative index for each configuration. This possibility would enable a ranking of the solutions and facilitate communication in selecting a system architecture. Some of the options are discussed below.

Typically, the project team will have at its disposal, for each possible architecture, the information condensed in Table. 6.

Table. 6: Available information for each system configuration

Equipment	Interfaces	Maturation Risks	Integration Risks
TRL for each piece of equipment.	IRL for each interface, considering the different integration types (E, M, T, D/C).	Risks related to the maturation of the technologies of components and interfaces; usually identified and characterized by an AD2 analysis.	Most relevant integration risks, for each interface, considering the different integration types (E, M, T, D/C).

As reviewed in Section II, the concept of a system readiness level, SRL, formed from the TRL and IRL values of system components and interfaces, is usually taken as a measure of the readiness level of the whole system. There are different proposed methods for the computation of the *SRL* index. This measure should be supplemented by a risk analysis, which is usually undertaken under the AD2 methodology preconized by NASA. The AD2 method has been designed to identify and characterize the risks associated with upgrading a system, subsystem, or component from a given TRL to a higher one. The AD2 methodology focuses on the following risk areas: design and analysis, manufacturing, software development, testing, and operations. The framework proposed in this work may be interpreted as proposing that the AD2 methodology be complemented by a risk analysis dedicated to identifying and characterizing the risks associated with the integration of a given system configuration, providing, in principle, an additional set of risks that complements the set of risks provided by the AD2 methodology.

A measure of the integration risk for each architecture may be constructed as follows. For each interface and integration type, a Technical Difficulty Factor (TDF) is computed from the fractions of N, L, and M/H assessments in the complete set of responses as:

$$freq_q(o) = \left(\frac{1}{N_a}\right)\sum_{l=1}^{N_a}\left(\frac{1}{9}\right)\sum_{m=1}^{9} Y_{mql}^{o}, \qquad (3)$$

$$freq_q(o) = \left(\frac{1}{9}\right)\sum_{m=1}^{9} y_{mq}^{o}, \qquad (4)$$

$$TDF_q = freq_q(N) * W_N + freq_q(L) * W_L + freq_q(M/H) * W_{M/H}\ , \qquad (5)$$

where Y_{mql}^{o} has been defined in (1), N_a is the number of filled forms, $freq_q(o)$ gives the fraction of options o for the interface q considering all forms and risks, and q designates the different interfaces, including the multiplicities introduced by the different integration types. The index TDF_q, with values between W_N and $W_{M/H}$, expresses the severity of each considered risk on the integration of interface q: the larger the value of TDF_q, the larger the chance of difficulties in the integration of interface q, according to the project team. It gives a measure of the risk affecting the integration work associated with interface q. The set of interfaces ranked according to the index TDF_q providesan ordered list of the interfaces that the specialized project team considers most critical in the project's system integration effort. Similarly, as the index I_{mq} facilitates integration risk communication, the index TDF_q provides a straightforward way of communicating to the project hierarchy which interfaces are considered critical in the integration effort.

Averaging, now, the index TDF_q over all interfaces:

$$TDF = \left(\frac{1}{Q}\right)\sum_{q=1}^{Q} TDF_q\ , \qquad (6)$$

where Q is the number of interfaces, including the multiplicities introduced by the different integration types, defines an index with values between W_N and $W_{M/H}$ that gives a measure of the overall integration risk of the configuration for which it has been computed. Hence, ordering the studied architectures according to the corresponding values of *TDF* provides a ranked list of the architectures, from riskiest to least risky, according to the assessment of the specialized project team. Hence, the *TDF* index offers a straightforward way of communicating to the project hierarchy which architecture is considered most risky regarding the integration effort.

The indices I_{mq}, TDF_q and TDF provide information regarding the risks associated with the integration effort of each system architecture. In contrast, the indices *TRL* and *IRL* provide information regarding the maturity of equipment and interfaces, respectively. Next, a proposal for the composition of these metrics is discussed.

The interface attributes expressed by IRL_q and TDF_q provide a measure of the maturity and the integration risk associated with interface q, respectively. While the IRL_q index may be used to rank interfaces according to their maturity, the TDF_q index may be used to rank interfaces according to their integration risk. One question that naturally arises at this point is how to rank the system interfaces by composing the two attributes IRL_q and TDF_q. The problem of ranking a variable with multiple attributes has received much attention [36, 37, 38]. In most applications, a weighted multiplicative scoring is considered more reliable than a weighted additive scoring

[38].Along this line, a possible index for ranking interfaces, based on the attributes of maturity and integration risk, may be constructed from a multiplicative scoring function involving the indices of the corresponding attributes.

An appropriate function, with equal weight exponents for both attributes, may be expressed as:

$$RWIRL_q = IRL_q \; x \; (W_N + W_{M/H} - TDF_q), \qquad (7)$$
$$IRL_q \in \{1, 2, \dots, 9\},$$

where *q* designates the considered interface.

The scale for *TDF* has been reversed, aligning both attributes so that the value of the proposed index increases with increasing maturity and decreasing integration risk.

The $RWIRL_q$ index shall be used exclusively for ranking purposes. It may be considered as giving for interface *q*, at a given instant, a composite measure of both integration maturity and severity of perceived risks for its integration.

Using the $RWIRL_q$ indices, it is possible to rank the interfaces according to their relevance in terms of maturity and integration risks. The set of interfaces ranked according to the index $RWIRL_q$ provides a convenient way of communicating the most critical interfaces, regarding maturity and integration risks, to the project hierarchy.

Averaging, now, the index$RWIRL_q$over all interfaces:

$$RWIRL\_int = \left(\frac{1}{Q}\right)\sum_{q=1}^{Q} RWIRL_q \,, \qquad (8)$$

introduces an index that gives a measure of the overall integration maturity and integration risks associated with the considered system architecture. The risk-weighted interface readiness level index,$RWIRL\_int$,is a system-wide index that combines overall interface maturity with overall interface integration risk. It may have relevance in a decision-making process dedicated to selecting a system architecture.

Next, along the same lines, we discuss the definition of a system-wide index that incorporates the maturity of the components that define the system architecture.

Following the previous discussion, a weighted multiplicative scoring is defined for each equipment based on the attributes of (a) maturity of the equipment, (b) maturity of the equipment's interfaces, and (c) the interfaces' integration risk. Since a piece of equipment may have more than one interface, a possible scoring function may consider an average for the interfaces, as given by:

$$\overline{RWSRL_i} = TRL_i \; x \; \frac{1}{Q_i}\sum_{j \neq i} IRL_{ij} \; x \; (W_N + W_{M/H} - TDF_{ij}), \qquad (9)$$
$$= TRL_i \; x \; \overline{RWIRL_i}, \qquad (10)$$
$$TRL_i \in \{1, 2, \dots, 9\},$$
$$IRL_{ij} \in \{1, 2, \dots, 9\},$$

where:

$$\overline{RWIRL_i} = \frac{1}{Q_i}\sum_{j \neq i} RWIRL_{ij} \,, \qquad (11)$$

the pair *(ij)* labels interfaces in the system, identified through the system elements between which the interface exists, Q_i is the number of interfaces of element *i*,$IRL_{ij}$is the maturity of the interface between elements *i* and *j*, TDF_{ij} is the technical difficulty factor for the interface between elements *i* and *j*, and $TRL_i$is the technical readiness level of element *i*. A note on the convention is in place. Interfaces will be identified either through a simple ordinal index *q* or by a pair of indices (*ij*) indicating the system elements between which the interface exists. Thus, if *q* labels the interface between system elements *i* and *j*, both$RWIRL_q$ and $RWIRL_{ij}$ designate the same index corresponding to the interface between elements *i* and *j*. The same holds for the indices IRL_q and TDF_q. In (7), a prescription like the one followed by Ross [27]for the association of interface maturity with a system element has been observed: for a given system element *i*, the average of the indices $RWIRL_{ij}$,associated with the interfaces of element *i*, referred to as $\overline{RWIRL_i}$, has been taken as an "average" interface attribute associated with the element *i*. The index $\overline{RWIRL_i}$ may be used to rank equipment according to its interface maturity and the perceived difficulty of its integration into the system.

Like the previous indices, the index $\overline{RWSRL_i}$shall be used exclusively for ranking purposes. The index applies to system elements and may be considered as giving, at a given instant, a composite measure of (a) equipment maturity,(b) integration maturity of the equipment's interfaces, and (c) severity of perceived integration risks associated with the equipment's interfaces. Hence, through the $\overline{RWSRL_i}$ indices, it is possible to rank system architecture elements according to their relevance in terms of the aforementioned three elements' attributes.

An index that compounds, at a system level, the attributes of (a) maturity of the system's equipment, (b) maturity of interfaces, and (c) risk associated with the integration of interfaces may then be defined by:

$$RWSRL = \left(\frac{1}{n}\right)\sum_{i=1}^{n} \overline{RWSRL_i}, \qquad (12)$$

where n is the number of system elements. The *RWSRL* index is defined for each system architecture. It may be relevant in a decision-making process dedicated to selecting a system architecture when it may be employed to rank different architectures.

Similarly, an index that compounds interface maturity and equipment integration risk for a given system configuration may be defined as:

$$\overline{RWIRL} = \left(\frac{1}{n}\right)\sum_{i=1}^{n}\overline{RWIRL}_i\,. \qquad (13)$$

Both the indices $RWIRL\_int$ and $\overline{RWIRL}$ compound the attributes of interface maturity and interface risk of integration at a system level. The difference between them lies in the fact that while $RWIRL\_int$ is computed over all interfaces indistinctly, the index $\overline{RWIRL}$ is computed considering the partitioning of the interfaces among the system components, as seen from (11). The latter index, thus, depends on the configuration of the system and is, in principle, a more appropriate measure for ranking configurations according to interface maturity and perceived risk of integration of the configuration.

3.2 Step-by-step procedure for application of the proposed framework

Fig. 5 gives the methodology's step-by-step process to obtain the RWSRL of each architectural solution and other indices. The following sections detail each step.

3.2.1 STEP 1

The technical team shall identify the equipment pieces in the system with more than one candidate supplier and all possible architectural solutions, considering the possible combinations of candidate equipment.

3.2.2 STEP 2

All interfaces between system elements are identified, possibly using an N-squared diagram (N^2). The technical team then classifies each interface according to the integration characteristics depicted in Table. 7.

Table. 7: A proposed classification scheme for interfaces

TYPE OF INTEGRATION	SUBTYPES	DESCRIPTION
Mechanical (M)		Comprises the mechanical joints and fastenings between the pairs of elements; geometries, mass property and stiffness matching, etc.
Electrical (E)	Power (P) Ground (G)	Comprises the supply of power (voltage and current) and grounding between the pairs of elements.
Thermal (T)		Comprises the heat exchanges (conduction and radiation) and thermal insulation between the pairs of elements.
Data and Command (D/C)	Data (D) Command (C)	Interface involving the exchange of digital data and analog signals, such as telemetry and telecommands.

The classification given in the table provides a sufficiently broad characterization that encompasses usual integration challenges. Depending on the system, it may be convenient to distinguish between subtypes of integrations, as shown in Table. 7. Building more than one N2 diagram may also be necessary when there is more than one way to provide the same function through a different arrangement of candidate equipment.

Fig. 4 gives an example of a system with four elements represented in an N2 diagram as a function of the integration types between each pair of elements. The acronyms are defined in Table. 7.

Equipment A	M T G	M T G	M T G
	Equipment B	P D C	T
		Equipment C	P T
			Equipment D

Fig. 4: Example of mapping integrations types

Legend: M- Mechanical; T-Thermal; P- Power; G- Electrical Ground; D- Data; C-Command.

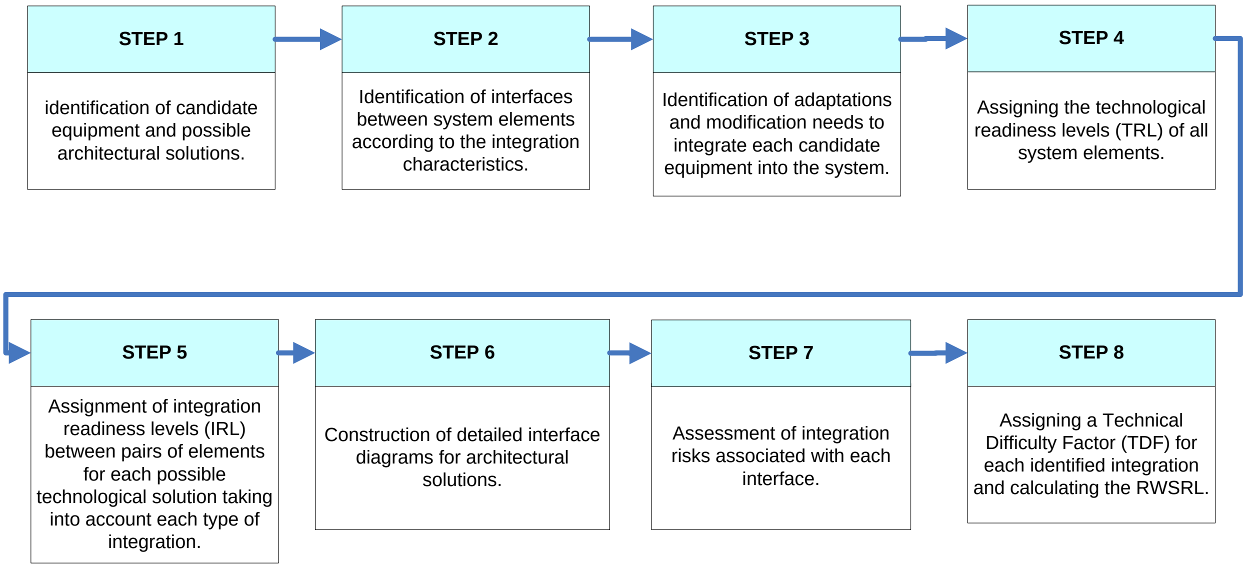


Fig. 5: Roadmap for using the RWSRL methodology

3.2.3 STEP 3

In this step, considering the requirements and preliminary design specifications, the technical team identifies adaptation and modification needs for integrating each candidate equipment into the system. Repercussions over other equipment and subsystems shall also be considered in this assessment. The need for further analysis addressing testing and modification of qualification status should also be contemplated. Usually, such studies are carried out by specialists in system engineering and assembly, integration, and testing (AIT) from the organization responsible for developing the system.

3.2.4 STEP 4

From the information gathered in Steps 2 and 3, the technical team shall assign a technology readiness level (TRL) index to the system components. According to the TRL philosophy, the TRL assessment gives the readiness level of each system element at a given moment of the project life cycle and for the environment prevailing at that moment [16, p. 15]. Hence, when the conditions holding at the time of a TRL assessment change, as in the case of equipment reuse in a different system, with eventual alterations in either the design, development process, targeted environment, or operations[16, p. 16], a reassessment of the *TRL* index will be necessary.

The TRL assignment may be carried out according to the classification given in Table. 8, which gives the ISO and ECSS standards for TRL classification.

Table. 8: ECSS-E-HB-11A [19] TRL scale

TRL	ISO 16290 standard
1	Basic principles observed and reported.
2	Technology concept and application formulated
3	Proof-of-concept
4	Component and breadboard ***functional verification*** in a laboratory environment
5	Component and breadboard ***critical function verification*** in a relevant environment
6	Model ***demonstrating the critical functions of the element*** in a relevant environment
7	***Model demonstrating the element performance for the operational*** environment
8	Actual system completed and ***accepted for flight ("flight qualified")***
9	Actual system "flight-proven" through successful mission operations

3.2.5 STEP 5

The technical team shall assign an interface readiness level (IRL) index to each identified interface, considering all possible architectures. The integration readiness levels (IRL) assignment for each interface type (M, E, T, and D/C), between each technology pair, shall consider the analyses carried out in Step 3. The assignment of an IRL index for each interface must be followed by evidence. Just as changes influence the TRL index, the IRL index is also susceptible to changes in the environment and must be reassessed in the event of modifications. Hence, the same pair of technologies may display different IRLs, either as a function of the type of integration (M, E, T, or D/C) or due to varying choices of candidate equipment. In summary, all integrations mapped in STEP 2 and all architectural solutions must undergo an evaluation regarding their maturity index. An example of decision criteria for the IRL assignment is given in Table. 9.

3.2.6 STEP 6

The technical team shall construct detailed interface diagrams for each system architecture, considering the different interface classifications given in Table. 7 (M, E, T, and D/C). The charts will be employed in identifying and analyzing the technical difficulties associated with each interface in the following steps. Fig. 6 displays an example of interface diagrams for a four-element system.

3.2.7 STEP 7

The technical team shall assess the integration risks associated with each interface using the assignment criteria given in Table. 2. The risk assessment must be carried out by subject matter experts and performed separately for each specified architecture. The assignment procedure makes use of specialized opinion. The evaluator goes through the nine criteria given in Table. 2 and identifies the best assessment for each interface. This procedure must be performed for all mapped integrations in the system.

Table. ***5*** shows a typical assessment form.

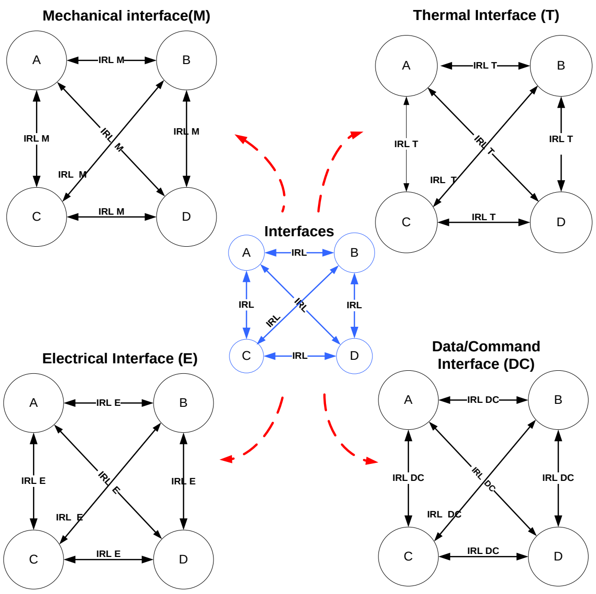


Fig. 6 Example of decomposition of integrations

All identified technical difficulties, with an assessment from *Low* to *Moderate or High* risk, must be accompanied by a brief description of the problem, from which the needs and magnitude of possible impacts, in terms of schedule and costs, may be assessed. Once a given architecture is chosen, these identified risks shall be treated and mitigated as part of the risk management of the technological solution selected.

3.2.8 STEP 8

In this step, the technical team shall compute the indices listed in Table. 10. The table lists indices whose rationale and form of computation are given in Section 3.1. All these indices are specific proposals of this article. The application of each index for ranking purposes is shown in the rightmost column of Table. 10.

We briefly review the methodology used to compute the TDF indices and their applications proposed in the present article. From each expert's assessment form, the frequencies of negligible (N), low (L), and moderate or high (M/H) assignments are computed. The TDF index for each interface is computed from the whole set of forms. The system-wide TDF index is then calculated as an average of the TDF indices for each interface. A new IRL matrix, referred to as the risk-weighted IRL matrix (RWIRL), is computed using (7).

Table. 9: Austin, M. F., & York, D. M. [19] Decision Criteria for Assessing Integration Readiness Level (IRL)

IRL	Definition	Evidence Description
0	No Integration	**No integration between specified components has been planned or intended.**
1	A high-level concept for integration has been identified.	**Principal integration technologies have been identified.** Top-level functional architecture and interface points have been defined. A high-level concept of operations and main use case has been started.
2	There is some level of specificity of requirements to characterize the interaction between components.	**Inputs/outputs for principal integration technologies/mediums are known, characterized, and documented.** Main interface requirements and specifications for integration technologies have been defined/drafted.
3	The detailed integration design has been defined to include all interface details.	**The detailed interface design has been documented.** System interface diagrams have been completed. Inventory of external interfaces is completed, and data engineering units are identified and recorded.
4	Validation of interrelated functions between integrating components in a laboratory environment.	**Integrating technologies (modules/functions/assemblies) has been successfully demonstrated in a laboratory/synthetic environment.** Data transport method(s) and specifications have been defined.
5	Validation of interrelated functions between integrating components in a suitable environment.	**Individual modules are tested to verify that the module components (functions) work together.** External interfaces are well defined (e.g., source, data formats, structure, content, method of support, etc.).
6	Validation of interrelated functions between integrating components in an appropriate end-to-end environment.	**The end-to-end Functionality of Systems Integration has been validated.** Data transmission tests were completed successfully.
7	System prototype integration demonstration in an operational high-fidelity environment.	**A fully integrated prototype has been successfully demonstrated in an actual or simulated operational environment.** Each system/software interface is tested individually under stressed and abnormal conditions. Interface, Data, and Functional Verification complete.
8	System integration completed and mission qualified through test and demonstration in an operational environment.	**A fully integrated system can meet overall mission requirements in an operational environment.** System interfaces qualified and functioning correctly in an operating environment.
9	System Integration is proven through successful mission-proven operations capabilities.	**A fully integrated system has demonstrated operational effectiveness and suitability in its intended or a representative operating environment.** Integration performance has been fully characterized and is consistent with user requirements.

The technical team shall choose the values of the weights W_N, W_L and $W_{M/H}$. A few prescriptions apply. For consistency, the value of the Technical Difficulty Factor index for an interface shall increase with increasing integration risk. Hence, the values given to the weights shall obey the relations:

$$W_N < W_L < W_{M/H}. \quad (14)$$

A natural choice for W_L is $\frac{1}{2}(W_N + W_{M/H})$. This choice considers a linear relation between option and weight.

Since the prescription for deriving system indices from system element indices is still an open issue [24, 22], below, we give alternative ways of computing the index RWSRL, following different prescriptions given in the literature.

Table. 10: Ranking indices and their use according to the proposed framework

I_{mq}(2)	Severity of risk *m* for the integration of interface *q*.	Ranking of the risks *m* for each interface *q*, according to risk severity.
TDF_q (5)	Technical Difficult Factor associated with interface *q*.	Ranking of interfaces *q* for a given system architecture, according to assessed interface risk of integration.
TDF (6)	System-wide Technical Difficult Factor.	Ranking of architectures, according to interface risk of integration.

$RWIRL_q$ (7)	Risk-weighted interface readiness level for interface *q*.	Ranking of the interfaces *q* for a given system architecture, according to composite measure of Interface Readiness Level and assessed interface risk of integration.
$RWIRL\_int$ (8)	System-wide risk-weighted interface readiness level.	Ranking of architectures, according to a composite measure of the attributes: (a) integration maturity of the equipment's interfaces and (b) severity of perceived integration risks of equipment's interfaces.
$\overline{RWIRL_i}$ (11)	Risk-weighted interface readiness level for equipment *i*.	Ranking of equipment according to its interface maturity and the perceived difficulty of its integration to the system.
$\overline{RWIRL}$ (13)	System-wide risk-weighted equipment readiness level for integration to the system.	Ranking of architectures according to equipment interface readiness for integration and perceived equipment integration risk.
$\overline{RWSRL_i}$ (9)	Risk-weighted readiness level for component *i*.	Ranking of the elements *i* of a system architecture according to a composite measure of the attributes equipment *i* maturity, integration maturity of the equipment *i* interfaces and severity of perceived integration risks associated with equipment *i* interfaces.
$RWSRL$ (12)	System-wide risk-weighted interface readiness level.	Ranking of architectures, according to a composite measure of the attributes of maturity of system's equipment, maturity of system's interfaces, and risk associated with the integration of system's interfaces.

3.2.8.1 Prescription by Ross

Here, the computation of the RWSRL is adapted from the SRL prescription given by Ross[27].

For a system with *n* elements, the complete prescription is as follows:

A –assign a TRL index to each system element, according to the scale given in Table 8, and express the system TRL in the form of a vector:

$$TRL = (trl_1, trl_{2,} \dots, trl_n)\ ; \qquad (15)$$

B –for the considered integration type (M, E, T or D/C) assign an IRL index to each identified interface in the system, according to the scale given in Table. 9, and express the result in matrix form as:

$$IRL^x = \begin{bmatrix} irl_{11}{}^x & irl_{12}{}^x \dots & irl_{1n}{}^x \\ irl_{21}{}^x & irl_{22}{}^x \dots & irl_{2n}{}^x \\ \vdots & & \\ irl_{n1}{}^x & irl_{n2}{}^x \dots & irl_{nn}{}^x \end{bmatrix}, \qquad (16)$$

where $irl_{ij}{}^x$ identifies the index corresponding to the system elements *i* and *j*, for the integration of type *x*; the diagonal elements, which give the index corresponding to the integration of a component with itself, are not used in this *SRL* computation prescription;

C –from the elements of the matrixIRL^x, compute the matrix below, the rationale of which is given in Section 3.1:

$$rwirl_{ij}^x = irl_{ij}^x\ x\ \frac{(W_N + W_{M/H} - TDF_{ij})}{(W_{M/H} - W_N)}, \qquad (17)$$

where TDF_{ij} is given by (5) and W_N and $W_{M/H}$are weights used in the interface risk analysis, defined in the Step 8;

D – compute the average value of the matrix elements in (17) as:

$$rwirl_i{}^x = \frac{1}{Q_i{}^x} \sum_{j \neq i} rwirl_{ij}{}^x\ , \qquad (18)$$

where Q_i^x is the number of non-zero elements in the considered line;

E – assign a manufacturing readiness level (MRL) index to each system element, according to a proper scale[27], and express the system MRL in the form of a vector:

$$MRL = \frac{1}{9}(mrl_1, mrl_{2,} \dots, mrl_n); \qquad (19)$$

F – compute the component system readiness level vector:

$$RWSRL^x = (rwsrl_1{}^x, rwsrl_{2,}{}^x \dots, rwsrl_n{}^x)\ , \qquad (20)$$

from the expression:

$$rwsrl_i{}^x = mrl_i \times trl_i \times \frac{1}{9} rwirl_i{}^x\ ; \qquad (21)$$

G – finally, compute the system readiness level$RWSRL^x$for the integration of type *x*, as the average of the elements of the vector given in (18):

$$RWSRL^x = \frac{1}{n} \sum_i rwsrl_i{}^x\ . \qquad (22)$$

It should be noted that the index $rwsrl_i{}^x$is equivalent to the index $\overline{RWSRL_i}$defined in (9), with the difference that here the type of integration *x* is being considered in an explicit way. When the system's topology does not change with the integration type (M, E, T or D/C) such explicit distinction is not necessary, being then possible to refer to each interface by a single index *q*, allowing for the multiplicity introduced by the different integration types.

The sequence of calculations leading to $RWSRL^x$ is carried out for the four types of integration. The RW*SRL* index of the system is finally computed from the equation:

$$RWSRL = \frac{RWSRL^M + RWSRL^E + RWSRL^T + RWSRL^{D/C}}{4} \quad (23)$$

The above computation should be carried out for all architecture solutions considered in the analysis.

It should be noted that (23) is equivalent to (12) if one considers the manufacturing readiness level for each component equal to its maximum value, i.e., if there are no limitations as regards manufacturing of system elements. Thus, the methodology given in Section 3.1, based on the theory of ranking a variable with multiple attributes [36, 37], is equivalent to the approach of Ross[27] for computing a system readiness level from the TRL and IRL of system elements.

3.2.8.2 Prescription by Sauser

The presentation given here is based on the work of Austin, M.F., & York, D. M. [19] and follows the prescription given by Sauser [8].

The complete prescription is as follows:

A – for each integration type *x* (M, E, T e D/C), assign an IRL index to each identified interface in the system, according to the scale given in Table. 9, and compute the $rwirl^x_{i,j}$ matrix from (17); in the present case, each diagonal element of IRL is assigned a value of 9;

B –the *RWSRL* vector is obtained by multiplying the normalized *TRL* vector by the normalized *RWIRL* matrix:

$$rwsrl_i^x = \sum_{j=1}^{n} \frac{rwirl_{ij}^x}{9} \text{ x } \frac{trl_j}{9}, \quad (24)$$

where the normalization factor is taken as the maximum of the corresponding assignment scales;

C –compute the *component RWSRL* vector from the expression:

$$crwsrl_i^x = rwsrl_i^x \,/\, m_i \,, \quad (25)$$

where m_i is the number of integrations of component i, as defined by the system architecture, including the integration of the component with itself;

D – the arithmetic average of the elements of the *component RWSRL* gives the *composite RWSRL*, which is interpreted as a measure of the system readiness, is then provided by:

$$RWSRL^x = \frac{1}{n}\sum_{i=1}^{n} crwsrl_i^x, \quad (26)$$

where *n* is the number of elements in the considered architecture.

The sequence of calculations must be repeated for the four types of integration, and the RWSRL of the system is, finally, computed from the equation (23):

IV. DISCUSSION

Multi-attribute Decision-making (MADM) is conceptually considered a branch of the area of Multi-criteria Decision-making (MCDM) in the field of Operations Research[39].

We note that the general form of a weighted multiplicative scoring function, with k attributes, is given by:

$$F = \prod_{i=1}^{k} a_i^{v_i}\,, \quad (24)$$

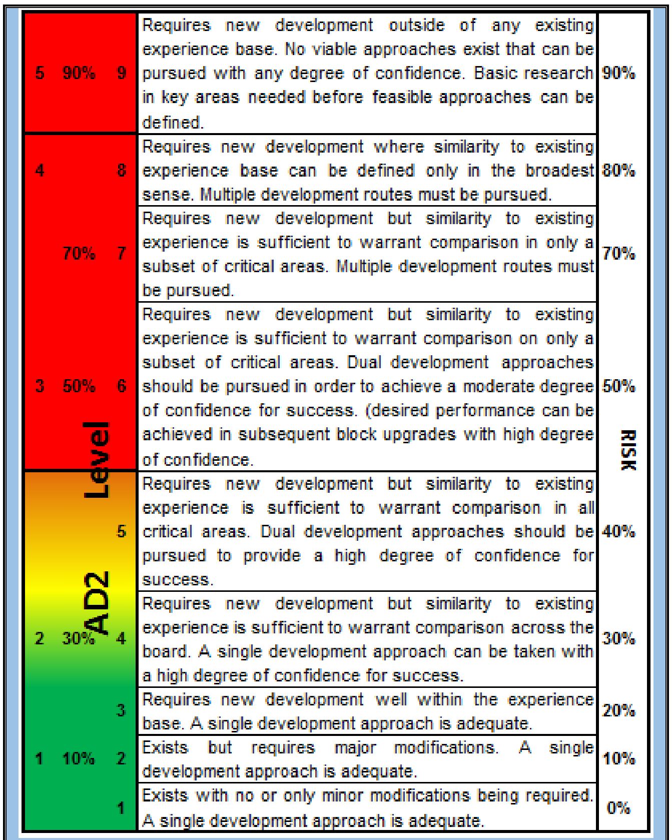
$$\sum_{i=1}^{k} v_i = 1, \quad (25)$$

where v_i designates the weight exponent of the index associated with the attribute a_i. If all v_i are equal, they may be dropped from (24) and (25). All the weighted multiplicative scoring functions defined in Section 3.1 use equal weight exponents. In principle, the formalism may be further developed through a judicious choice of the weight exponents, considering the specificities of the intended application. It should also be noted that the effective scoring functions leading to the indices *RWIRL* and *RWSRL* are composed of a mix of multiplicative and additive scoring functions. These indices should be carefully analyzed for each specific application, given the possible idiosyncrasies affecting additive scoring functions, as discussed in detail by Tofallis [38].

The framework given in this article has not explicitly considered an index for the attribute of technology maturation risks. Such risks might be assessed through an AD2 framework, as already discussed in Section 3.1. We emphasize that the AD2 methodology investigates the risk areas of design and analysis, manufacturing, software development, testing, and operations, which may be considered complementary to the risk area considered in the present framework. In principle, an index associated with the attributes associated with technology maturation risk might be devised and implemented following the concepts given in this article.

Fig. 7 shows the relation between the AD2 level scale and risk severity, represented by its two components: impact and probability. The chart in the lower part of the figure gives descriptions for the classification of risks' impact into five levels, while the upper chart gives the correspondence of each AD2 scale level with corresponding values of impact level and probability (severity).

The framework proposed in this article may be interpreted as a version of the AD2 framework, adapted for the assessment of integration risks. To further ascertain this point, Fig. 8 gives the relation between the assessment of the selected integration risks listed in Table. 2 and risk severity, represented by the pair impact and probability. Comparing with the charts given in Fig. 7, it is seen that the present framework and the AD2 framework are conceptually equivalent, although applied to the different risk areas.



Consequence

Level	Technical	Schedule	Schedule
1	Minimal or no consequence to	Minimal or no impact	Minimal or no impact
2	Minor reduction in technical performance or supportability, can be tolerated with little or no impact on the program	Able to meet key dates. Slip <*month(s)	Budget increase or unit production cost increases. <**(1% of Budget)
3	Moderate reduction in technical performance or supportability with limited impact on program objectives	Minor schedule slip. Able to meet key milestones with no schedule float Slip <*month(s) Sub-system slip<*month(s) plus available float	Budget increase or unit production cost increases. <**(5% of Budget)
4	Significant degradation in technical performance or major shortfall in supportability; may jeopardize program success	Program critical path affected Slip <*month(s)	Budget increase or unit production cost increases. <**(10% of Budget)
5	Severe degradation in technical performance. Cannot meet KPP or key technical/supportability threshold; will jeopardize program success	Cannot meet key program milestones Slip <*month(s)	Budget increase or unit production cost increases. >**(10% of Budget)

DOD Consequence Descriptions

Fig. 7: Relation between the AD2 framework and the risk management process in a project. Adapted from Bilbro[7]

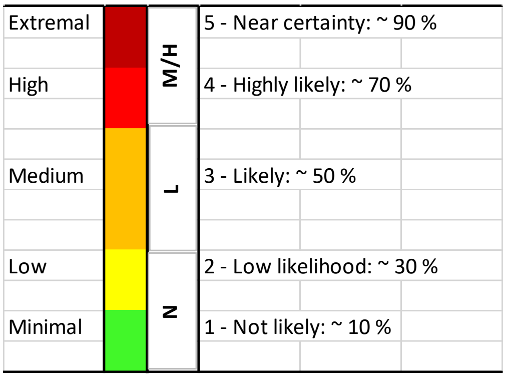


Fig. 8: Relation between the proposed framework and the risk management process in a project. Colors indicate the severity level, according to the scale depicted in Fig. 3

Using the concepts introduced in this article makes it possible to associate an index to each of the risks investigated in the AD2 framework. As an illustration, Fig. 9 gives a possible correspondence betweenAD2 scale levels with the computation concepts introduced in this article.

AD2 levels	Risk Options	Weights
9	M/H	$W_{M/H}$
8		
7		
6	L	W_L
5		
4		
3	N	W_N
2		
1		

Fig. 9: Possible relation between the AD2 scale levels and the framework presented in this article.

Legend: N: negligible; L: low; M/H: moderate to high

In order to accommodate the AD2 scheme into the present framework, it would then be necessary to formulate the AD2 specific questions as risk statements and unfold them into three excluding possibilities, following the logic illustrated in Table. 2. Instead of a form for each interface, there would be a form for each element of the system work breakdown structure (WBS). From this point on, a TDF factor would then be computed for each WBS element and composed with the other attributes, as discussed in Section 3.1, giving origin to different indices. This additional step would complete the procedure of the framework proposed in this article. The outcome is a project technology assessment framework that composes the following technology readiness assessments and risks: technology readiness level of equipment, technology readiness level of interfaces, technology maturation risks, and integration risks.

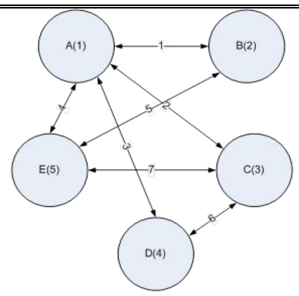
V. RESULTS

This section illustrates the application of the proposed framework. Two examples are developed in order to show that the proposed methodology can capture relevant information from the system through indices, which are consistent with the information from the analysis.

5.1 Example 1

An example involving one interface type, or a configuration in which the architectures for the different interface types are topologically equivalent, is presented in the following. Table. 11 shows the parameter values used in the example.

Table. 11: Parameters' values for Example 1

Number of Evaluators (N_a)	32				
Number of system components (n)	5				
Number of interfaces (Q)	7				
W_N	0.8				
W_L	1.0				
$W_{M/H}$	1.2				
TRL	3	9	9	4	7
IRL matrix	0	7	9	3	7
		0	0	0	1
			0	3	2
				0	0
					0

The assessment of the 7 interfaces (Q) by 32evaluators (Na) has been simulated by randomly selecting an assignment for each risk. Fig. 10 gives the aggregated result for each risk, for Interface 1, as an example. Similar results are obtained for the other interfaces.

Identification: INTERFACE 1				
Risk	N	L	M/H	I_{mq}
1 - Know-how	8	15	9	0,9777
2 - GSE	17	9	6	0,9893
3 -	7	19	6	0,9955
4 - Workload	12	8	12	0,9911
5 - Training	11	8	13	0,9893
6 - Nonconformance	12	13	7	1,0179
7 - Interface	12	9	11	1,0000
8 - Verification	11	10	11	1,0205
9 - Complexity	4	13	15	1,0134
Frequency	0,33	0,33	0,34	
Weighting factors	0,80	1,00	1,20	
Criterion's weight	0,26	0,33	0,41	
TDF				**0,99944**

Fig. 10: Aggregated result for Interface 1, according to the simulated assessment of Na = 32 evaluators. The cells in red and in green identify what would be the most and least severe risks, as assessed by the technical personnel

The rightmost column shows the values of the index$I_{mq}$for each risk. The values give a measure, for ranking purposes only, of the relevance of the corresponding risk (*m*) for the considered interface integration (*q*). The highlighted maximum (red) and minimum (green) values correspond to the most and least severe risks for the assessed interface.

Interface	*IRL*	TDF_q	$RWIRL_q$
1	7	0,9972	7,0194
2	9	0,9944	9,0500
3	3	1,0021	2,9938
4	7	0,9986	7,0097
5	1	1,0063	0,9938
6	3	0,9896	3,0313
7	2	1,0076	1,9847
TDF		0,9994	
RWIRL_int			4,5832

Fig. 11: The indices TDF_q and $RWIRL_q$ are given for each interface for the simulated example discussed in the text. The system-wide indices TDF and RWIRL_int are also shown

The IRL, TDF_q and $RWIRL_q$ indices for each interface are given in Fig. 11, with the least and most favorable cases identified with red and green colors. The figure also lists the corresponding system-wide indices, *TDF* and *RWIRL_int*, for the simulated configuration. When considering only the difficulties perceived by the technical team, i.e., when considering only the index *TDF*, this simulated example would show that interface 7, with IRL equal to 2, would rank first in risk severity when compared to the other interfaces. Interface 6, although with a low IRL value, equal to 3, would present the most favorable situation within the considered set of risks. When composing integration risk with maturity, interface 5, with the lowest IRL, equal to 1, would be the most challenging interface, while interface 2, with IRL equal to 9, would represent the most favorable case.

Equipment / Interfaces	***TRL***	$\overline{RWSRL_i}$	$\overline{RWIRL_i}$
1 / 1-2-3-4	3	19,5547	6,5182
2 / 1-5	9	36,0594	4,0066
3 / 2-6-7	9	42,1979	4,6887
4 / 3-6	4	12,0500	3,0125
5 / 4-5-7	7	23,3058	3,3294
RWSRL		**26,63355**	

Fig. 12: The index RWSRLi for each equipment is given. The last line shows the system-wide index RWSRL

Fig. 12 gives the values of $RWSRL_i$ andthe average values of the risk-weighted integration level, $\overline{RWIRL_i}$, associated with each element *i*. The figure also gives the value of the system-wide index *RWSRL*. In the simulated scenario, with random assessments of each interface, the system component ranked as most critical has TRL 4 and coincides with the element that shows the most unfavorable value for the index $\overline{RWIRL_i}$.

5.2 Example 2

The hypothetical case of a system with five component equipment with four alternatives for one of the components is now studied through simulation.

It is assumed that the system displays different configurations for different interface types. Fig. 13 shows the assumed configurations for the four types of interfaces defined in Table. 4 (M, E, T, and D/C). Ordinal numbers identify interfaces, while system components are identified by letters, sequentially from A to E. Alternative candidate equipment, for the "A" position, are identified by A1 through A4.

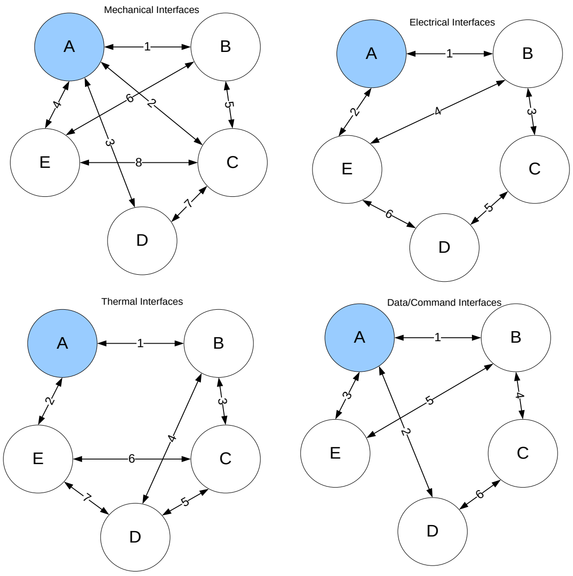


Fig. 13: System decomposed into the four types of interfaces.

TRL and IRL values for equipment and interfaces have been randomly selected and are displayed in Fig. 14, with the provision that the IRL indices are the same for each type of interface (M, E, T, and D/C), even when switching between candidates for the "A" position. Also, it is assumed that the insertion of candidate equipment does not affect the TRL of the remaining system equipment B, C, D, and E. The assessment of the 9 risks by 3 specialists has also been randomly selected. Although the specific simulated situation would seldom be verified in actual cases, the conceptual case of choosing a piece of equipment among several possibilities is quite common.

IRL	A1	B	C	D	E
A1	0	1	7	5	9
B	1	0	3	0	3
C	7	3	0	3	6
D	5	0	3	0	6
E	9	3	6	6	0

IRL	A2	B	C	D	E
A2	0	7	0	0	2
B	7	0	2	0	6
C	0	2	0	3	0
D	0	0	3	0	7
E	2	6	0	7	0

IRL	A3	B	C	D	E
A3	0	5	0	0	4
B	5	0	9	8	0
C	0	9	0	8	3
D	0	8	8	0	6
E	4	0	3	6	0

IRL	A4	B	C	D	E
A4	0	6	0	8	8
B	6	0	9	0	6
C	0	9	0	7	0
D	8	0	7	0	0
E	8	6	0	0	0

Equip.	A1	A2	A3	A4	B	C	D	E
TRL	6	6	7	7	6	6	5	7

Fig. 14: Simulation input data.

Fig. 15 lists the$RWSRL$ index for each type of interface, referred to as $RWSRL(x)$, with $x \in (M, E, T, D/C)$, as well as the system$RWSRL$ for each architectural solution formed with the candidate components. It is seen that the solution with the equipment A4 presents the highest $RWSRL$ value. Comparing the $RWSRL(x)$ values among the different solutions, it is observed that Solution 4 ranks first, except for the D/C interface type, when Solution 3 ranks first. Concerning the TDF index, which would give a measure of integration risk for each configuration as perceived by the technical team, Solution 4 also ranks first as the preferred solution (lower risk). It is also seen from Fig. 14 that the alternatives A3 and A4 show TRL values equal to 7, superior to the value 6 for alternatives A1 and A2. From Fig. 14, it is also seen that the average IRL for component A4, equal to 22/3, is superior to the equivalent values for alternatives A1 to A3, equal to 22/4, 9/2, and 9/2, respectively. Thus, from the analysis of the basic input indices it would be expected that alternative 4 would fare better than the other alternatives. The virtue of methodologies belonging to the MADM class is to condense, through one or more indices, computed straightforwardly, information that would be obtained through detailed analysis. In this example, the proposed methodology would give, through the language of ranking indices, the same answer as would be obtained by a detailed analysis of the problem.

	Composition		RWSRL sys	TDF sys
Architecture Solution 1	A1-B-C-D-E			
	RWSRL (M)	28,3062	33,0733	1,0123
	RWSRL (E)	25,6551		
	RWSRL (T)	35,6578		
	RWSRL (D/C)	42,6741		
	Composition		RWSRL sys	TDF sys
Architecture Solution 2	A2-B-C-D-E			
	RWSRL (M)	27,9211	33,5081	0,9990
	RWSRL (E)	26,5911		
	RWSRL (T)	36,2514		
	RWSRL (D/C)	43,2689		
	Composition		RWSRL sys	TDF sys
Architecture Solution 3	A3-B-C-D-E			
	RWSRL (M)	28,5743	34,6057	1,0045
	RWSRL (E)	27,4289		
	RWSRL (T)	36,0402		
	RWSRL (D/C)	46,3795		
	Composition		RWSRL sys	TDF sys
Architecture Solution 4	A4-B-C-D-E			
	RWSRL (M)	29,9407	34,9820	0,9890
	RWSRL (E)	27,8131		
	RWSRL (T)	36,4193		
	RWSRL (D/C)	45,7548		

Fig. 15: Result of the ranking simulation of the architectural solutions formed between candidates A1, A2, A3 and A4.

The TDF index also synthesizes relevant information for the project risk management process, pointing out which risks require more attention from project management.

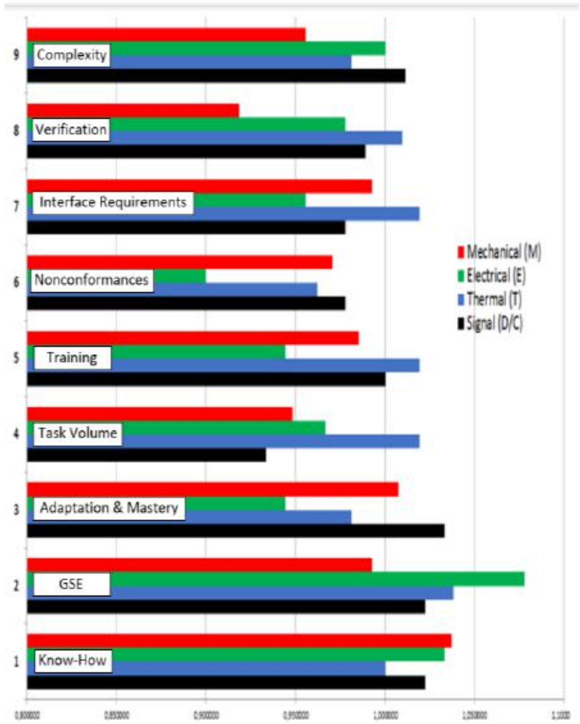


Fig. 16: Ranking result of the architecture solution 4 by risk type and by interface type

Fig. ***16*** shows a comparison of the relevance of each assessed risk for each interface type as given by the I_{mq} index, for Solution 4. For instance, risk 9, "Complexity", is ranked first for the Signal interface, while risk "Verification" ranks first for the Thermal interface. Among all risks, the risk GSE ranks first, for the case of an Electrical interface type, according to the technical team risk assessment leading to the *TDF* index.

When the objective is to understand which type of interface presents the highest integration risk, the Technical Difficulty Factor (TDF) may be computed for each interface type. This index makes it possible to rank the different interface types according to their integration risk. For the example under scrutiny, Fig. 17shows that the simulated data would indicate that the thermal and signal interface types would require greater attention than the other interface types in the integration effort.

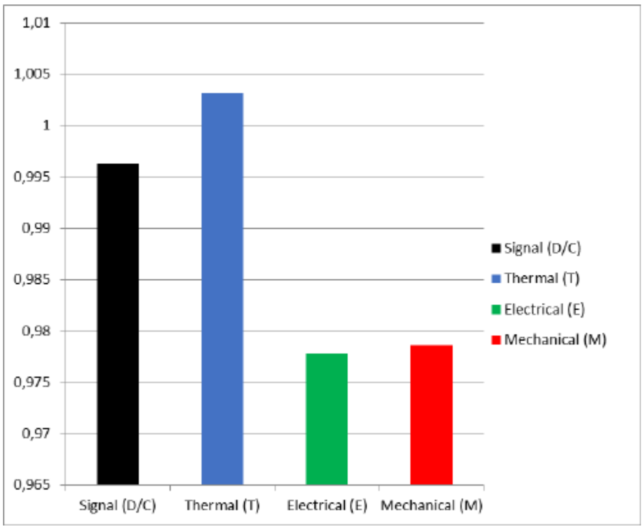


Fig. 17: Ranking of TDF by interface types of architecture solution.

VI. CONCLUSION

The methodology given in this article aims to propose ranking indices that measure the integration risks of system architectures, to be compounded with system technology and interface readiness levels indices to define multiple attribute indices adequate for the ranking of different system architectures. This objective has been implemented as follows.

The integration risk assessment is based on specialized opinion. In the methodology version presented here, a selection of nine integration risks, covering a broad range of disciplines, is submitted, in the format of an individual form survey, to the assessment of systems engineering personnel, specialty engineers, project managers, and assembly, integration and testing specialists. The detailed risk information that emerges from the survey is translated into an index, referred to as the Technical Difficulty Factor (TDF), which gives a measure of integration risk severity for each interface.

Through the composition of this index with the set of IRL indices, a new composite index, referred to as Risk-weighted Integration Readiness Level (RWIRL), is defined for each interface. The RWIRL indices are then compounded with the equipment TRL indices, giving origin to a new set of indices, referred to as RWSRLi, which may be used to rank system equipment according to the attributes of equipment maturity, interface maturity, and integration risk. From the set of RWSRLi indices, a system-wide index, termed Risk-weighted System Readiness Level (RWSRL), is derived, which may be used to rank different system architectures, considering the attributes mentioned above.

With additional effort, through a procedure indicated in the article, the TDF index may be compounded with a conveniently defined AD2 index, thus defining a compounded TDF risk index, which now considers integration risks and technology maturation risks. Following the procedure already delineated above, one obtains equivalent indices as those above defined, incorporating both maturity and risk information.

The outcome is a project technology assessment framework that composes the following elements: equipment readiness level, technology readiness level of interfaces, technology maturation risks, and integration risks.

It is pointed out that the RWSRL methodology proposed in this article deals with the definition of ranking indices and their applications. Values of *computed* indices have meaning only for comparison purposes; it is not possible to assign them a scale as in the TRL, IRL, and SRL methodologies. The variability of the results generated will always depend on the values adopted for the weights W_N, $W_{L,}$ and $W_{(M/H)}$. The values may be tailored according to the conveniences of the intended application. This will not affect the result whenever linearity between them is observed.

Although conceived for application in space projects` Phases A and B, the RWSRL methodology may be applicable, in principle, to a wide range of project types, at different life cycle stages, for instance, whenever a decision among multiple supply options is necessary or as an input for related RIDM processes. The proposed risk assessment model is sufficiently generic to be tailored to other design applications.

The various ranking indices proposed in the article provide potentially relevant data for project management, not only as a selection tool among candidate items for the system's composition but also as an input for a conventional CRM process for detailing and mitigating risks. The proposed risk assessment may indicate the areas and aspects related to system integration that require great or special attention in the system design.

There is a relationship between the AD2 scale levels and the structure presented in this article, as shown in Fig. 8 and Fig. 9. It can be argued that both tools work similarly and that the AD2 and RWSRL methodologies may work as complementary frameworks.

The RWSRL metric captures the potential risks at a given moment of the project, as perceived by the technical team. Beyond their utility in decision-making processes, the proposed indices provide an effective communication bridge between systems teams and project management. They convey appropriate identification and characterization of integration difficulties and risks foreseen in each evaluated architecture solution.

The utility of multi-attribute decision-making methodologies as applied to projects is to condense, through one or more indices, computed straightforwardly and systematically, information that would be obtained through detailed analysis. The examples given in Section 3 indicate that the proposed methodology is successful in providing through the language of ranking indices information that would be obtained only through a detailed analysis.

REFERENCES

[1] Reeves, J. D., Eveleigh, T., Holzer, T., & Sarkani, S. (2012, March). The impact of early design phase risk identification biases on space system project performance. In 2012 IEEE International Systems Conference SysCon 2012 (pp. 1-8). IEEE

[2] Dezfuli, H., Benjamin, A., Everett, C., Maggio, G., Stamatelatos, M., Youngblood, R., ... & Williams, R. (2011). NASA risk management handbook (No. NASA/SP-2011-3422-Version-1.0).

[3] Sauser, B. J., Long, M., Forbes, E., & McGrory, S. E. (2009, July). 3.1. 1 Defining an Integration Readiness Level for Defense Acquisition. In INCOSE International Symposium (Vol. 19, No. 1, pp. 352-367).

[4] Mankins, J. C. (2009). Technology readiness assessments: A retrospective. Acta Astronautica, 65(9-10), 1216-1223.

[5] Bilbro, J. W. (2006). Systematic Assessment of the Program/Project Impacts of Technological Advancement and Insertion. George C. Marshall Space Flight Center, Dec.

[6] Mankins, J. C. (1998). Research & development degree of difficulty (R&D3). White Paper, March, 10.

[7] Bilbro, J. W. (2008). Using the Advancement Degree of Difficulty (AD2) as an input to Risk Management. JB CONSULTING INTERNATIONAL HUNTSVILLE AL.

[8] Sauser, B., Verma, D., Ramirez-Marquez, J., & Gove, R. (2006, April). From TRL to SRL: The concept of systems readiness levels. In Conference on Systems Engineering Research, Los Angeles, CA (pp. 1-10). sn.

[9] Silva Jr, A. C. (2011). Desenvolvimento integrado de sistemas espaciais-Design for AIT-Projeto para Montagem, Integraçao e Teste de Satélites D4AIT (Doctoral dissertation, PhD thesis, Instituto Tecnológico de Aeronáutica).

[10] Hirshorn, S., & Jefferies, S. (2016). Final report of the NASA Technology Readiness Assessment (TRA) study team (No. HQ-E-DAA-TN43005).

[11] Mankins, J. C. (1995). Technology readiness levels. White Paper, April, 6(1995), 1995.

[12] Beauchamp, P. M., Frerking, M. A., Kimmel, B., Kline, T. R., Vassigh, K. K., Willard, D. E., ... & Trenkle, T. G. (2020). Technology Readiness Assessment Best Practices Guide.

[13] Mankins, J. C. (2002). Approaches to strategic research and technology (R&T) analysis and road mapping. Acta Astronautica, 51(1-9), 3-21.

[14] Valerdi, R., & Kohl, R. J. (2004, March). An approach to technology risk management. In Engineering Systems Division Symposium (Vol. 3, pp. 29-31).

[15] Magnaye, R. B., Sauser, B. J., & Ramirez-Marquez, J. E. (2010). System development planning using readiness levels in a cost of development minimization model. Systems Engineering, 13(4), 311-323.

[16] Secretariat, E. (2016). ECSS-E-HB-11A DIR1, Space engineering-Technology readiness (TRL) guidelines. draft standard, ESA-ESTEC, Requirements & Standards Division, Noordwijk, The Netherlands.

[17] Sauser, B., Ramirez-Marquez, J., Henry, D., Dimarzio, D., & Rosen, J. (2007). Methods for estimating system readiness levels. School of Systems and Enterprises White Paper, 1, 1-40.

[18] Sauser, B. J., Ramirez-Marquez, J. E., Henry, D., & DiMarzio, D. (2008). A system maturity index for the systems engineering life cycle. International Journal of Industrial and Systems Engineering, 3(6), 673-691.

[19] Austin, M. F., & York, D. M. (2015). System Readiness Assessment (SRA) an illustrative example. Procedia Computer Science, 44, 486-496.

[20] Austin, M. F., & York, D. M. (2016). System Readiness Assessment (SRA) a Vade Mecum. In Complex Systems Design & Management (pp. 53-68). Springer, Cham.

[21] Gove, R., & Uzdzinski, J. (2013). A performance-based system maturity assessment framework. Procedia Computer Science, 16, 688-697.

[22] London, M. A., Holzer, T. H., Eveleigh, T. J., & Sarkani, S. (2014). Incidence matrix approach for calculating readiness levels. Journal of Systems Science and Systems Engineering, 23(4), 377-403.

[23] McConkie, E., Mazzuchi, T. A., Sarkani, S., & Marchette, D. (2013). Mathematical properties of system readiness levels. Systems Engineering, 16(4), 391-400.

[24] Kujawski, E. (2012). Analysis and critique of the system readiness level. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 43(4), 979-987.

[25] Azizian, N., Mazzuchi, T., Sarkani, S., & Rico, D. F. (2011). A framework for evaluating technology readiness, system quality, and program performance of US DoD acquisitions. Systems Engineering, 14(4), 410-426.

[26] Azizian, N., Sarkani, S., & Mazzuchi, T. (2009, October). A comprehensive review and analysis of maturity assessment approaches for improved decision support to achieve efficient defense acquisition. In Proceedings of the World Congress on Engineering and Computer Science (Vol. 2, pp. 20-22). San Francisco.

[27] Ross, S. (2016). Application of System and Integration Readiness Levels to Department of Defense Research and Development (Postprint). AIR FORCE RESEARCH LAB KIRTLAND AFB NM KIRTLAND AFB United States.

[28] Hirshorn, S. (2016). NASA System Engineering Handbook SP-2016-6105 Rev2.

[29] Tan, W., Ramirez-Marquez, J., & Sauser, B. (2011). A probabilistic approach to system maturity assessment. Systems Engineering, 14(3), 279-293.

[30] NASA, N. (2010). Risk-Informed Decision Making Handbook. NASA/SP-2010-576 Version 1.0, NASA Headquarters, Washington, DC.

[31] Dubos, G. F., Saleh, J. H., & Braun, R. (2008). Technology readiness level, schedule risk, and slippage in spacecraft design. Journal of Spacecraft and Rockets, 45(4), 836-842.

[32] Ramirez-Marquez, J. E., & Sauser, B. J. (2009). System development planning via system maturity optimization. IEEE Transactions on Engineering Management, 56(3), 533-548.

[33] Bilbro, J. W. (2007). A suite of tools for technology assessment. JB CONSULTING INTERNATIONAL HUNTSVILLE AL.

[34] Mankins, J. C. (2009). Technology readiness and risk assessments: A new approach. Acta Astronautica, 65(9-10), 1208-1215.

[35] VOXCO, "Ordinal survey questions," VOXCO, [Online]. Available: https://www.voxco.com/blog/ordinal-survey-questions [Accessed on 06.03.2022 March 2022]

[36] Lu, J., Han, J., Hu, Y., & Zhang, G. (2016). Multilevel decision-making: A survey. Information Sciences, 346, 463-487.

[37] Leoneti, A. B. (2016). Considerations regarding the choice of ranking multiple criteria decision making methods. Pesquisa Operacional, 36, 259-277.

[38] Tofallis, C. (2014). Add or multiply? A tutorial on ranking and choosing with multiple criteria. INFORMS Transactions on education, 14(3), 109-119.

[39] Tzeng, G. H., & Huang, J. J. (2011). Multiple attribute decision making: methods and applications. CRC press.