Towards Full Systems Integration Readiness Assessment

Mohammad Rajabalinejad
Department of Design, production, and Management, University of Twente, the Netherlands.
E-mail: M.Rajabalinejad@utwente.nl

This study presents a systematic approach toward the full system integration readiness assessment (SIRA). In engineering practices, integration is often seen as combination of two or more components in technical systems. Such a view represents the physical or structural integration. Next to the structural aspects, the behaviour and function of products or systems need to be designed for integration. For optimal results, a product needs to be integrated not only structurally but also operationally and functionally across the full life cycle.

Keywords: Integration, hierarchy, behaviour, system integration readiness assessment, SIRA

1. Introduction

Three fundamental properties of every system are function(s), structure, and behaviour across the full lifecycle, and the complete performance of such a system can be evaluated against these properties. System functions can be summarised as operate, maintain, or manage the resources or as observe, orient, decide and act according to Hitchins (2007). System structure defines boundaries for a system. The boundaries can be static or change over time. They can be conceptual or physical. The physical boundary defines a system as a set of parts that are combined in order to deliver the expected functions. System behaviour indicates the state change for a system, its response, or exchange of information, energy, and resources. For delivering the expected performances, all the fundamental system properties must properly take place. For the satisfactory technical-performance of a system (TPM), system function, structure, and behaviour need to be considered according to Miller et al. (2010).

This study focuses on integration as the subject of interest because integration issues can impact project schedule and as a result can lead to extra cost. The reasons for this are many observations wherein a reliable technology or system fails to integrate with a reliable operating system. Several examples of integration issues for the rail transport are presented in Rajabalinejad (2018).

The hypothesis for this study is that the full integration is an important performance measure for systems of interest. In this context, integration is beyond the technical combination of system parts. The study discusses system structure, system behaviour, and system function with respect to integration maturity. For integration, however, most of engineering practices focus on structural aspects and less attentions are being paid on functions or behaviour. Best practices recommend tools and techniques for creating products or systems which are properly designed, flawlessly integrated, and the expected functionalities are optimally delivered.

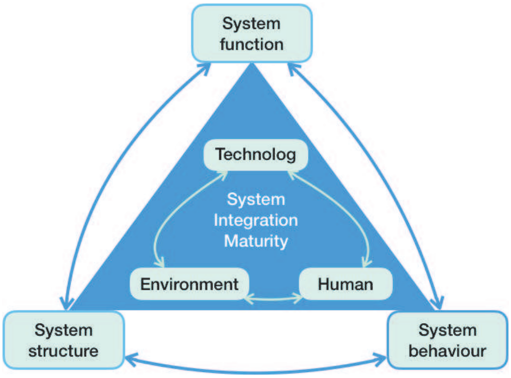

Fig. 1. Three fundamental aspects for systems integration.

The paper aims to construct basis for evaluation of system integration as a key performance indicator. As shown by Figure 1, the underlying assumption for this study is that the performance or maturity of systems integration can be evaluated over three fundamental system properties which are structure, function, and behaviour. The ingredients for systems integration are people, system, and its environment as discussed in Rajabalinejad (2019b).

Section 2 explains the system structure and

Proceedings of the 29th European Safety and Reliability Conference.
Edited by Michael Beer and Enrico Zio

Published by Research Publishing, Singapore.
ISBN: 978-981-11-2724-3; doi:10.3850/978-981-11-2724-3_0241-cd

suggests several levels for clarifying the hierarchical connection of a component to the environment. Section 3 reviews the system function and discusses several levels for functional-wise integration of the system across its full lifecycle. Section 4 explains the importance of system behaviour in integration and suggests seven levels for system behaviour & operation.

2. System Hierarchy

A hierarchy is an arrangement of items (objects, names, values, categories, etc.) in which the items are represented as being ”above,” ”below,” or ”at the same level as” one another. Levels in a hierarchy may also represent authority, control or ownership of lower levels (command structure) according to Oxford English Dictionary. The international community of systems engineers (INCOSE) acknowledge the challenge of defining the system structure with respect to the required level of details. It observes system hierarchy as organisational representation of system structure. It is important to note that the depth of hierarchy is adjusted to fit the complexity or nature of the system of interest, and a system may have more focus on some levels and less focus on some other levels.

The logical or conceptual hierarchy is used in different disciplines such as risk assessment or system governance as presented for example by Leveson (2015). The logic of hierarchy is closely related to logic of integration. In the engineering practices, integration appears after creation. This is a logical approach where first the functionalities are identified, the systems and subsystems are designed, and then the components or subsystems are built and then integrated. Systems engineering discipline pays special attention to integration. It defines the purpose of the integration process as “to synthesise a set of system elements into a realised system (product or service) that satisfies system requirements, architecture, and design”, see Walden et al. (2015). Furthermore, through its recommended V model, widely used across different industries, the right-half focuses on integration, verification, and validation. In this context, integration focuses on combining the system components or subsystems.

Here in this paper, the sequence system, sub-system, and component is used for referring to the breakdown of a system into smaller parts. The word system and subsystem is interchangeable used as practiced by EN (2015). This section provides a conceptual overview of system hierarchy aiming to present an organisational (both internal and external) view for the structure of the system of interest. This facilitates the view of integration maturity beyond a specific level as the full hierarchical chain often requires considerations. This conceptual overview helps understanding the system as an integral whole which is composed of components and interacts with the environment. This provides a logical relation of each component with the environment, and it is different from the component lifecycle perspective presenting that every component comes directly back to the environment after the end of his life.

Next subsections suggests a hierarchical view for integration for seven levels which are subsystem, system, human-system, system of systems, socio-technical systems, political system, and environmental system.

2.1. Subsystems Integration

Subsystems integration refers to combination of two or more components. In other words, integration of components leads to subsystems. Both subsystems and components are parts of a system and cannot independently function. Components or subsystems integration are often the earliest action in physical integration. For example, the V model suggests starting integration from this level. Integration of components occurs often in production or assembly stage.

2.2. Systems Integration

Systems engineering community defines a system as “an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements” according to Walden et al. (2015).

The SE handbook defines integration as a technical process for integrating the elements of a system. In this context, a successful system integration leads to a system that works and delivers the required functionalities without any failure. The failure in this process is seen as defect of a component or interface. At this level, the focus is mainly on components, subsystems, or interfaces. Through this approach, the integration of human and system becomes an issue because it is not a completely technical process. The SE handbook recognises that integration of human and system is not a technical process and recommends focusing on human systems integration (HSI) across the design or engineering of systems.

2.3. Human-Systems Integration

Human systems integration (HSI) is the interdisciplinary technical and management process for integrating human considerations within and across all system elements according to ISO 29148:2011. HSI focuses on the human, an integral element of every system, over the system life cycle. It is an essential enabler to SE practice as it promotes a “total system” approach that includes humans, technology (e.g. hardware, software), the operational context, and the necessary interfaces between and among the elements to make them all work in harmony, see Walden et al. (2015).

Next to technical integration, the SE handbook highlights human system integration (HSI) within the scope of the systems integration. HSI ensures consideration of the human in the system capability definition and system development. In this context, human is considered as an element of the system, and its integration with system must by fully considered. HSI considers domains such as human factors engineering (human performance, human interface, user centred design), workload (normal and emergency), training (skill, education, attitude), personnel (knowledge, attitudes, career progression), working condition and health (ergonomics, occupational standards, and hazard and accident avoidance), see Walden et al. (2015). In other words, HSI aims to address the human expectations, proper user interfaces, trained personnel, and under-control performances.

2.4. System of Systems (SoS) Integration

System of systems is a combination of two or more independent systems. A “system of systems” (SoS) is a system whose elements are managerially and/or operationally independent systems according to the systems engineering handbook. As results, the interoperability of the integrated systems or subsystems usually is not achievable by an individual system alone. The relations among a system and other systems have been discussed elsewhere for example by Mo Jamshidi in the context of System of Systems, see Jamshidi (2008). He considers integration as the key viability of any system of systems. This means that systems can communicate and interact through different interfaces e.g. hardware, software, etc. In this context, a system uses services from other systems or delivers services to other systems. This requires collaboration among different organisations. For delivering optimal results, having shared objectives among organisations, co-creation of desired capabilities, and co-integration of interoperable services are key factors to success according to Rajabalinejad and Dongen (2018); Madni and Sievers (2014). The effects of a system and its behaviour on the related-environment have been discussed through the safety-related references which will be further discussed through the next section.

2.5. Socio-technical Integration

System of systems needs to integrate with the society in order to optimally deliver its services. SoS requires to obey national or international regulations in order to be able to deliver its services. Besides, the cultural aspects play a major role for its acceptance within a society, see Woo and Vicente (2003). For example, the communication language, accepted norms and value, or expected services have impacts on system of systems and its sustainable performance according to Davis et al. (2013).

2.6. Political Integration

Socio-technical systems need to be controlled by the government and follow the societal values and policies. Organisational chains of responsibility, authority, and communication for executing measurement and control mechanisms to effectively drive the organisation and enable people to perform roles their respective roles and responsibilities, see Cantor (2006).

2.7. Global Integration

Human societies have shared considerations which can be presented through for example international regulations or global expectations. Global considerations such as use of green energy, reducing fossil fuels, and minimal CO2 emission are among these. Proper integration of SoS with the environment must take into account these aspects, see White (1988).

3. System Functions

Function is broadly used across different disciplines e.g. engineering, finance, human resources, etc. Function is the ability to achieve a desired effect under specified (performance) standards and conditions through combinations of ways and means (activities and resources) to perform a set of activities according to ISO (2007). In systems theory, a function is defined by transformation of input flows to output flows delivering the required performances. Therefore, the output of functions contribute to system goals and objectives. Function can be an action, a task, or an activity for achieving a desired outcome according to Hitchins (2007). In the context of systems engineering, functional integration describes how a system is functionally integrated both internally and externally. Such a system requires to process information, energy, or other inputs to deliver responses. It is important to note that functional integration frequently relies on interconnectivity among subsystems or systems.

This section reviews the chain of functions which are in line with system hierarchy. The fundamental assumption is that a system can properly integrate with its environment if it functionally integrates with human and with its enabling, collaborating, or competing systems. It is therefore important to define different states of the system from functional perspective and in different levels of hierarchy across its full lifecycle. A properly designed system needs to carefully consider system malfunctions, related safety functions, and temporal extra pressure on the system.

Next subsection describes system-related functions at different levels of system hierarchy. These functions are verifying subsystems functionality, delivering required system-functions, acting in compliance with standards, interacting with other systems, delivering required services, and performing in a resilient and sustainable way.

3.1. Sub-functional Integration

Subsystems require to deliver the expected functions which are often called sub-functions. Subsystems need to be tested and verified against the requirements for sub-functions. Any state of combining different pieces or components e.g. assembly or production are examples for this state. Subsystems, however, can not function independently by definition.

3.2. Functional Integration

A functional system requires to perform as intended and under the stated conditions. To ensure system functionality over time, the system needs to be reliable and well maintained. A majority of standards focus on defining standard functionalities for systems or subsystems or validating their quality as discussed next.

3.3. Compliant Integration

A compliant system is in compliance with relevant rules and (inter)national regulations and offer services that meet (at least) minimal safety requirements. Regulations and standards often target reliable services with accepted level of quality, safety, or security. For example, standards such as ISO 55000 focus on the quality control for performing functions, see ISO (2014). IEC 61508 a seminal standard for functional safety delivered in several parts. Part 1 of this standard addresses issues on system safety validation and system integration (tests) including architecture, software, and PE integration tests, see IEC (2010).

3.4. Robust Integration

Robustness is the inherent strength or resistance in a system to withstand external demands without degradation or loss of functionality according to Florin and Linkov (2016). ISO/IEC/IEEE describes robustness as the degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions, see IEEE (2017). This insightful definition describes that the focus at this stage is beyond the system and on the function of a system in the context of its dynamic environment. In other words, a system that is functional and compliant requires to be robust and have strength against changes in its environment which includes the competing, or collaborating systems. At this level, a system should be able to tolerate changes in its environment and remain functional.

3.5. Resilient Integration

Resilient is the ability to adapt to changing conditions and prepare for, withstand, and rapidly recover from disruption according to DHS (2010). INCOSE defines resilience as the ”ability to maintain capability in the face of adversity”. When a system is serving the society, there is a need for resiliency, see Florin and Linkov (2016).

3.6. Sustainable Integration

When the system is in balance with its environment, it is a sustainable system. Sustainable development considers the needs of stakeholders, enabling systems, and future generations, see Walden et al. (2015). Environmental considerations can be incorporated into the product/system life cycle through for example eco design practices, see Pigossoa et al. (2013). Sustainable development demands for not only proper design theories and practices but also power an political influence according to Egelston (2013). From the design perspective, human environment and usability are keys for sustainable development, see Issa and Isaias (2015).

3.7. Environmental Integration

The integration of environmental concerns into design, continuous monitoring of the environmental status, and analysis of disposal impact are the key elements of success, see Walden et al. (2015).

The United States Environmental Protection Agency (EPA) formulates the green engineering practice in which the design, commercialisation and use of processes and products that are feasible and economical while they reduce the generation of pollution and minimise the risk to human health and the environment. An example application for future design of green production system is provided by Gabbar (2007).

4. System Operation

Operation is beyond the behaviour of the technical system. Systems behaviour is a change which leads to events in itself or other systems. Thus, action, reaction or response may constitute behaviour in some cases, see Ackoff (1971). This definition associates behaviour with an emergent outcome of (complex) deployed system, more analogue to human/animal behaviour. Taking this view, the whole organism has behaviour but not any of its element systems; e.g., cars have behaviour (when driven by people), engines have functions.

4.1. Suboperational Integration

Subordinate operation. The system is partially operating, and therefore its services are partially available.

4.2. Operational Integration

Availability is the probability that a repairable system or system element is operational at a given point in time, under a given set of environmental conditions The system delivers is available for delivering functions. The environment in which systems are deployed. The problem or opportunity in response to which the system has been developed, exists in this environment.

4.3. Safe Integration

Safety is "freedom from those conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment" according to DoD (2012). Safe integration is a level of integration where the system, human, and the environment of the system are properly addressed. A safely integrated system is in compliance with both national and international regulations and offer services that meet (at least) minimal safety requirements, see Rajabalinejad (2019a). Regulations and standards often target safe integration too (see for example the European Directive for Railways). ISO 12100, the reference standard for safety of machinery, pays special attention to safety matters during assembly of a machine or its integration with the surrounding environment, see ISO (2010).

It is important to note that these conditions are not limited to a specific period of time when the system elements are synthesised. Safe behaviour offers maximum predictable protection to the operator by limiting hazards.

4.4. Interoperable Integration

Interoperability is one the characteristics of system of systems, see Madni and Sievers (2014). A dynamic configuration of resources (people, technology, organisations and shared information) that creates and delivers value between the provider and the customer through services according to IBM definition. Interoperability becomes a key factor for success for public services such as transportation and mobility, see Rajabalinejad and Dongen (2018).

4.5. Satisfying Integration

A system is successfully implemented when it can satisfy its needs and objectives. Those are not only technical goals but also include stakeholders, organisational, and business objectives. System level objective include interfaces with other systems (system of systems) and interoperable services that fit to user requirements. User here include the primary user of the system (customers or internal user) and the user of other systems (external user). At this level of system operation the needs of both internal and external customers require to be met. In other words, at the business level operation the needs of internal as well as the needs for external stakeholders (stakeholders of other systems) have to be met. This fits into the scope of a system fit-for-use and satisfying customers and users according to Hitchins (2007). Resiliency is important at this stage because stakeholders need to avoid business interruption, see Rose et al. (2007).

4.6. Economic Integration

Sustainable and consolidated businesses and services are fundamental to sustain competitive advantages across industries and form circular economy, see Pieroni et al. (2019). This requires clear business goals and objectives, and broad integration of process, workflow, governance, business process, and social services forming the ecosystem of services.

4.7. Harmonic Integration

According to the definition of integration, a system is properly integrated when it behaves in harmony with its environment, see Rajabalinejad (2019a). Harmonisation of the laws at the global scale, but it will be very naive to think that the technological risks are all managed by the same means that they were created, see North (2012). Happiness, health, and wealth and the insights from cognitive social science and behaviour are important aspects for connecting humans to nature, and these will not be achieved by technological solutions only.

Organically inspired alternatives and their integration with technology based solutions can increase the accuracy and efficiency and reduce risks leading to sustainable solutions, see Hogue (2010).

5. Conclusions

Table 1 presents an overview for different levels of integration hierarchy and the related functional and operational aspects for a system. This table lists the main aspects for the full system integration readiness assessment (SIRA). The underlying assumption for SIRA is that a successful system integration requires integration in the system structure, function, and behaviour. In other words, chain of structure (system hierarchy), chain of functions, and chain of behaviour need to be taken into account for a complete system integration. Although the recommended practice is more complete than common practices such as RAMS or RAMSSHEEP (standing for reliability, availability, safety, security, health, environment, economy, and politics), comprehensiveness of the SIRA approach is subject to further research.

Acknowledgement

The author acknowledges the support of Dutch Railways, ProRail, and HTSM through the framework of the SIRA project (see https://integration.engineering).

References

Ackoff, R. L. (1971). Towards a system of systems concepts. Management Science, 17(11), 661–671.

Cantor, M. (2006). Cantor, m. 2006. estimation variance and governance. in ibm developerworks. accessed on 15 september 2011. IBM developerWorks. Available online at http://www.ibm.com Available at http://www.ibm.com.

Davis, K., T. Mazzuchi, and S. Sarkani (2013). Architecting technology transitions: A sustainability-oriented sociotechnical approach. Systems Engineering 16(2), 193–212.

DHS (2010). Department of homeland security risk lexicon. Available online at http://www.dhs.gov.

DoD (2012). Mil-std-882e: 2012 department of defense standard practice system safety. MIL-STD-882E.

Egelston, D. A. E. (2013). Sustainable Development. Sprinter.

EN (2015). En 50126 railway applications - the specification and demonstration of reliability, availability, maintainability and safety (rams) - part 1: Generic rams process.

Florin, M. and I. Linkov (2016). IRGC resource guide on resilience. Lausanne: EPFL International Risk Governance Center (IRGC).: © EPFL International Risk Governance Center, 2016.

Gabbar, H. A. (2007). Design of virtual plant environment for future generation green production systems. Systems Engineering 10(2), 155–166.

Hitchins, D. (2007). Systems Engineering: A 21st Century Systems Methodology. The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England: John Wiley and Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England.

Hogue, A. (2010). When technology fails: Getting back to nature. American Psychological Association 17(1).

IEC (2010). Iec 61508-1 functional safety of electrical/electronic/programmable electronic safety-related systems – part 1: General requirements.

IEEE (2017). Ieee 24765 systems and software engineering — vocabulary.

ISO (2007). Iso/iec 26702 ieee std 1220-2005 2007 systems engineering — application and management of the systems engineering process.

ISO (2010). En-iso 12100:2010 safety of machinery - general principles for design - risk assessment and risk reduction.

ISO (2014). Nen-iso 55000:2014 (e) asset management - overview, principles and terminology.

Issa, T. and P. Isaias (2015). Sustainable Design HCI, Usability and Environmental Concerns. Springer.

Jamshidi, M. (2008). System of systems engineering new challenges for the 21' century. IEEE Aerospace and Electronic Systems Magazine 23(5).

Leveson, N. (2015). A systems approach to risk management through leading safety indicators. Reliability Engineering and System Safety 136, 17–34.

Table 1. An overview for the full system integration readiness assessment (SIRA).

Hierarchy of system	Function of system	Behaviour of system
Global: system and interfaces with international policies and regulations	Environmental: in balance with the natural or green environment	Harmonic: healthy, organic, human & nature
Politics: system and interfaces with policies and regulations	Sustainable: needs of stakeholders, enabling systems, and future generations	Economic: consolidated businesses, cost and benefits
Socio-technical systems: system & interfaces with society	Resilient: recover from disruption, no-interruption	Satisfying: real user experience, business operation
System of systems: systems and interfaces with other systems	Robust: strength against changes in related systems	Interoperable: interoperable services across system of systems
Human-systems: Human and interfaces with system	Compliant: standards & regulations e.g. RAMSS	Safe: safety, security, privacy, cultural & managerial aspects
Technical system(s): subsystems and their interfaces	Functional: full functionalities	Operational: available services
Subsystem(s): components and their interfaces	Subfunctional: partially functional	Suboperational: partially operational

Madni, A. M. and M. Sievers (2014). System of systems integration: Key considerations and challenges. Systems Engineering 17(3), 330–347.

Miller, C., R. S. Carson, S. Fowler, D. J. Gantzer, and G. Roedler (2010). Systems Engineering Measurement Primer A Basic Introduction to Measurement Concepts and Use for Systems Engineering. San Diego, CA 92111-2222: INCOSE.

North, D. W. (2012). The better angels of our nature: Why violence has declined. Risk Analysis 32(7), 1270–1272.

Pieroni, M. P. P., T. C. McAloone, and D. C. A. Pigosso (2019). Business model innovation for circular economy and sustainability: A review of approaches. Journal of Cleaner Production 215, 198–216.

Pigossoa, D. C., H. Rozenfelda, and T. C. McAlooneb (2013). Ecodesign maturity model: a management framework to support ecodesign implementation into manufacturing companies. Journal of Cleaner Production 59.

Rajabalinejad, M. (2018). System integration: Challenges and opportunities. In System of Systems Engineering, Paris, France. IEEE.

Rajabalinejad, M. (2019a). Safe integration for system of systems: The safety cube theory. In System of Systems Engineering, Alaska, USA.

Rajabalinejad, M. (2019b). A systemic approach for safe integration of products and systems. In M. Rajabalinejad (Ed.), The Ninth International Conference on Performance, Safety and Robustness in Complex Systems and Applications, Valencia. IARIA.

Rajabalinejad, M. and L. v. Dongen (2018). Framing success: the netherlands railways experience. International Journal of System of Systems Engineering 8(4), 313–329.

Rose, A., G. Adosu, and S. Y. Liao (2007). Business interruption impacts on the electric power system resilience to a total blackout of a terrorist attack of los angeles: Customer. Risk Analysis 27(3), 513–531.

Walden, D. d., G. J. Roedler, K. J. Forsberg, R. D. Hamelin, and T. M. Shortell (2015). Systems Engineering Handbook A Guide For System LiFe Cycle Processes And Activities. International Council on Systems Engineering (INCOSE).

White, R. K. (1988). Risks, concerns, and social legislation - forces that led to laws on health, safety, and the environment - priest,wc. Risk Analysis 8(3), 471–471.

Woo, D. M. and K. J. Vicente (2003). Sociotechnical systems, risk management, and public health: comparing the north battleford and walkerton outbreaks. Reliability Engineering and System Safety 80(3), 253–269.