12th INCOSE SA Systems Engineering Conference
ISBN 978-0-620-72719-8

Everything You Thought You Knew about Validation and Verification is Probably Dodgy

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Abstract

Even though validation and verification are commonly-used system life cycle processes, the literature shows that much confusion surrounds them. Using the current definitions of validation and verification, its three foundation concepts are: Which artifact is to be validated or verified? Which other artifacts need to be examined to provide objective evidence to declare that artifact to be validated or verified? What objective evidence should be obtained and how? A content analysis is performed on all relevant generally-accepted international standards since the 1960s in quality management and in system engineering to investigate the answers to the three research questions assumed by those definitions. Without changing the definitions of validation and verification, the logically-consistent answers are: Only requirements-of-interest for a to-be-developed system can be validated or verified. A requirement-of-interest is declared validated or verified if all downstream requirements (or characteristics) derived from it jointly fulfill that requirement-of-interest. Objective evidence to confirm that the requirement-of-interest has been fulfilled is obtained by means of either analysis, or inspection, or demonstration or test of a functional or physical model of those downstream derived requirements. The notion of endorsement is introduced. The concepts underlying validation and verification are clarified.

Key words ISO 15288, ISO 9000, validation and verification (V&V), requirement, characteristic, conformity, endorsement, Vee-model.

1 Introduction and Problem Statement

The concept of verification has been around since at least 1961 [MIL-STD-109A:1961] with validation added in the 1980s [IEEE Std-729:1983]. Validation and verification (V&V) concepts have evolved, not least since at roughly the same time the notions of requirements and their elicitation and management have been formalized; a clear distinction has been made between business/mission requirements and stakeholder requirements, in contrast to system requirements; and various relationships between requirements have been defined, for instance the trace relationships.

Nevertheless, although V&V terms are commonly used [Adcock 2016], their precise meaning is confusing. For instance, Wymore observed [Wymore 2002]: “There seems to be a great deal of confusion about the meaning of verification and validation (V&V). There are some authors who apparently regard these two terms as synonymous, others who seem to be only vaguely aware of the differences. Some even appear to believe that V&V is one word! And then there is confusion as to what should be validated, what should be verified, and when.” The INCOSE Requirements Working Group commented [INCOSE RWG:2015]: “While these {V&V} terms are commonly used, the true meaning of the concepts represented

This is a conference version of the paper *Unscrambling the Concepts of Validation and Verification* submitted for review to Systems Engineering, the Journal of INCOSE, on 13 June 2016.

ISBN 978-0-620-72719-8

in each are often misunderstood and the terms are often used interchangeably. Both terms are very ambiguous unless preceded by a modifier which clearly indicates what concept the term is referring to, specifically verification or validation of requirements, of the design, or of the system under development. The concepts are very different depending on the modifier. When using these terms, it should be clear as to which concept is being referred to: requirement verification or requirement validation; design verification or design validation; system verification or system validation."

Even a superficial examination of the conflicting definitions of V&V in various documents leads to confusion. However, definitions of V&V are merely an articulation of the underlying concepts of V&V—the mental model of thinking and reasoning around which these definitions have been written. Any confusion about V&V is either caused by poor wording of those definitions, or by muddled thinking about these underlying concepts.

This paper describes how this confusion could be clarified. A key point is that the focus of V&V should be on a single requirement-of-interest, not on a set of requirements-of-interest and not on a system-of-interest. The insight presented by this paper is that the unit of analysis for validating or verifying a requirement-of-interest is a set of downstream requirements or characteristics. This paper also describes how objective evidence should be obtained to confirm fulfillment of the requirement-of-interest. Without departing from the currently-accepted definitions of V&V, the confusion surrounding V&V will be cleared up in a logically-consistent way.

The research questions, and research method, are described in Section 2. Section 3 defines requirements, intentions and characteristics, and Section 4 describes the Vee-model context of requirements and characteristics. Section 5 discusses the current definitions of V&V. Section 6 explains that the V&V unit of analysis is a requirement or a characteristic. Section 7 discusses that a downstream requirement or characteristic should be examined. Section 8 describes the research results. Section 9 addresses the V&V of an individual requirement and Section 10 defines the various V&V activities. Section 11 describes ten V&V instances during the concept, development, production, utilization and support stages of the system life cycle. Section 12 distinguishes validation from verification. Section 13 examines the recommendations of the INCOSE Requirements Working Group. Section 14 introduces the concept of endorsement, and Section 15 illustrates V&V with a culinary example. Section 16 summarises the conclusions.

2 Research Questions and Research Method

The current generally-accepted definitions of validation and verification are [ISO 9000:2015] [ISO/IEC/IEEE 15288:2015]:

Validation Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.

Verification Confirmation, through the provision of objective evidence, that specified requirements have been fulfilled.

What precisely is the difference between V&V and a conformity? The current definition of a conformity is "a fulfillment of a requirement" [ISO 9000:2015 clause 3.6.11[1]]. But is that not the same as the definition for verification? This is discussed in Section 9.

Examining these two definitions, and indeed many previous V&V definitions, raises three important issues that became research questions defined below. A preliminary discussion is combined with each research question.

[1] A note to the definition states: In English the term "conformance" is synonymous but deprecated, in other words the term "conformance" is tolerated but not recommended.

ISBN 978-0-620-72719-8

Research question 1 What precisely is to be validated or verified? The definitions clearly state that when requirements-of-interest have been fulfilled then those requirements-of-interest have been V&V. For conceptual clarity it turns out that a single requirement-of-interest should be V&V, not a set of requirements-of-interest. After all, each requirement-of-interest has its own V&V activity. Only if many requirements-of-interest have a common V&V activity that will be performed at the same instance, does it make sense to consider a set of requirements-of-interest. Although this seems a trivial issue, that will be the point of departure. A related question is: A requirement-of-interest for what? For a to-be-developed system? Or for the life cycle processes of that system, for instance the processes defined in ISO 15288? The definitions are silent on this. Research question 1 is discussed in Section 8.

Research question 2 Which artifact is to be examined to obtain objective evidence to determine whether a requirement-of-interest has been fulfilled? In other words, what is the unit of analysis of a requirement-of-interest? The obvious answer would be the to-be-developed system that implements the requirement-of-interest, except that its granularity is too poor since it implements numerous requirements-of-interest. But a to-be-developed system does not yet exist, and by the time an as-built system is available, would V&V not be too late to be of much use, except for acceptance purposes? The only artifacts of the to-be-developed system available earlier are requirements and characteristics—should those be used for providing evidence to determine whether a requirement-of-interest has been fulfilled?

A related question is: Relative to the requirement-of-interest, are the requirements to be examined to provide objective evidence upstream or downstream, or is it perhaps the requirement-of-interest itself? Research question 2 is discussed in Section 6.

Research question 3 What objective evidence about those requirements and characteristics should be provided? How should that evidence be obtained? What role do the four standard V&V activities—analysis, inspection, demonstration and test—play, given that those activities cannot be applied to a requirement? Can those V&V activities be applied to a functional or physical model of that requirement or characteristic? Of course, after the manufacture of either a prototype system or a production system, as-is characteristics can be inspected, demonstrated or tested to obtain objective evidence. Research question 3 is discussed in Section 9.

A thorough literature survey over the past thirty years would be impractical due to the large number of publications concerning V&V during that period, hence a content analysis of the V&V definitions was used as research method [Leedy, Ormrod 2010]. In fact, content analysis turns out to be the only research method suitable for these research questions. The first assumption of this research is that the definitions from generally-accepted international standards on quality management and on system engineering, as well as their predecessor standards, reveal the concepts of V&V. A qualitative content analysis was performed on those standards by means of a detailed and systematic examination. Since the intent of any definition is to explicitly describe, delineate, demarcate and standardize a concept, content coding was irrelevant and a manual approach to content analysis was used. Nevertheless this content analysis was not a mechanistic process, since the context of V&V leads to related concepts concerning requirements, characteristics, intentions and the Vee-model, and that complicates matters. This content analysis is described and discussed, see for instance Table I, to ensure that the research is comprehensive and transparent.

If various standards are not harmonized, which standard should have precedence? The second assumption of this research is that ISO standards have precedence over other standards, that a standard has precedence over a handbook or a guidebook, and that a more recent standard has precedence over an older standard. For instance, ISO 9000 [ISO 9000:2015] is the world's most widely-recognized quality management standard, with more that one million organizations in more than 170 countries certified to ISO 9001 [Wikipedia 2016]. ISO 9000 would thus have precedence over ISO 15288 [ISO/IEC/IEEE 15288:2015], which in turn would have precedence over the INCOSE Systems Engineering Handbook that follows it.

It turns out that the content analysis of the V&V definitions in the relevant quality management and system engineering standards provides no single convincing answer to the research questions, and thus does not remove the confusion; see Section 8. However, the research questions, content analysis and research results do expose the fault lines causing that confusion. That provides confidence to provide sensible and informed answers to the research questions based on the research results and straightforward logical reasoning. But that needs a sharpening of terminology discussed in Sections 3 and 4.

3 Requirements and Characteristics

> We are trapped by language to such a degree that every attempt to formulate insight is a play on words. — Niels Bohr
>
> The limits of my language are the limits of my world. — Ludwig Wittgenstein

The quotations illustrate that language and vocabulary are crucial in our understanding of a concept. Different ways of naming become different ways of thinking and understanding, and then become different ways of reasoning.

Two definitions fully define the nature of a requirement: A requirement is a statement that translates or expresses a need and its associated constraints and conditions [ISO/IEC/IEEE 15288:2015]. A requirement is a statement that identifies a product or process operational, functional, or design characteristic[2] or constraint, which is unambiguous, testable or measurable, and necessary for product or process acceptability (by consumers or internal quality assurance guidelines) [IEEE 1220:2005].

As the second definition implies, a requirement shall satisfy the so-called requirements for a requirement, sometimes known as the characteristics of a requirement: The requirement shall be necessary, implementation-free, non-ambiguous, traceable, achievable, clear, verifiable, correct, singular and concise [Kar et al, 1996] [INCOSE RWG:2015] [ISO/IEC/IEEE 29148:2011 clause 5.2.5]. If a statement does not satisfy those requirements of a requirement, then it is not a requirement.

What do we call a statement before it becomes a requirement? Even though ISO 29148 does not formally define an intention, it states: “An intention, sometimes known as a need, goal, or objective, is an incomplete requirement that needs additional effort to convert it into a requirement” [ISO/IEC/IEEE 29148:2011]. An intention does not yet satisfy the requirements of a requirement[3]. For instance, a thought in a stakeholder’s mind is an intention, but not a requirement. If a mere thought were a requirement, the concept of a requirement would be meaningless. For instance, both TBDs (to be determined) and TBCs (to be confirmed) are intentions, since they do not satisfy the requirements for a requirement.

The introduction of the formal definition of a requirement was meant as a supplement to, not a replacement for, the term characteristic; where a requirement is to-be and a characteristic as-is. The classic definition is [MIL-STD-109A:1961]: A characteristic is a physical,

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[2] The term “characteristic” should be replaced by “need” or “expectation”.

[3] An intention is also known as a raw requirement, in contrast to a well-formed requirement [IEEE 1233:1998] [ISO/IEC 24765:2010]. “A well-formed requirement … can be validated … and is qualified by measurable conditions and bounded by constraints,” in other words it is a requirement.

[4] The phrase in (the author’s) italics is usually added.

[5] This is essentially the definition of a quality characteristic [ISO 9000:2015 clause 3.10.2]. ISO 15288:2015 states: “A quality characteristic is an inherent characteristic of a product, process, or system related to a requirement.” To emphasize that a characteristic is not a to-be requirement this paper uses the term “as-is characteristic”.

ISBN 978-0-620-72719-8

chemical, visual, functional or any other identifiable property of a product *by which it can be assessed for conformance to a requirement*[4]. A more refined definition can be developed from [ISO 9000:2015[5]]: A quality characteristic is the physical as-is manifestation or embodiment of a to-be requirement[6]. A characteristic obviously can no longer be a requirement. A characteristic that satisfies its associated requirement is known as conforming, else it would be nonconforming [ISO 9000:2015]. Incidentally, many of the definitions quoted in this paper are "common terms and core definitions for ISO management system standards" [ISO 9000:2015] and are thus not open for debate. These definitions include requirement, conformity, nonconformity, performance, measurement and process.

Although a characteristic has been defined as a physical as-is characteristic, the principle of emergence [Checkland 1999] [Adcock 2016], see Section 4, implies that a functional as-is characteristic is created by the interaction between many physical as-is characteristics.

A requirement may obviously change many times during its life cycle and thus demands a rigorous configuration management process. A system is merely whatever may be needed to satisfy the business/mission requirements and the constraints and other requirements imposed by stakeholders. A set of related requirements is typically contained in a specification.

4 The Vee-model Provides the Context for Requirements and Characteristics

To deepen understanding, different categories of requirements and characteristics should be identified; see Figure 1.

Design-to requirements The term design-to requirement is used in the sense of "Design this system so that it can do this, that, or the other." Design-to requirements are mainly functional requirements that define a behaviour or operation, although it may also include physical requirements such as a mass or dimension constraint. A design-to functional requirement has associated performance requirements that quantitatively define how well the function is to be performed. For instance, "The aircraft shall fly" is a functional design-to requirement, with associated performance requirements: "Maximum flight speed M 1.5 ± 0.1"; "Unrefuelled flight duration 4 ± ¼ h"; "Operating flight ceiling 30 000 ± 1 000 ft". Each of the performance requirements should be individually verifiable, meaning that a finite cost-effective process exists with which a person or a tool can check that the requirement is fulfilled by the system [IEEE 830:1984]. A more recent definition of verifiable is that the requirement can be checked for correctness by a person or a tool [ISO/IEC 24765:2010]. A functional requirement is verifiable only in a binary sense—the function is either present or not—once all of its associated performance requirements have been individually verified. In practice, a functional requirement is declared verified once all its performance requirements have been declared verified. When the term design-to requirement is used in this paper, it thus means a functional requirement with its associated performance requirements.

Build-to requirement The term build-to requirement is used in the sense of "Build this system so that it looks like this, that, or the other." Build-to requirements are almost always physical requirements that define material features such as composition, dimensions, finishes, form, fit and their respective tolerances. For instance, "The rod shall have a diameter of 10.0 ± 1.0 mm"; or "The gear shall be manufactured from 17-4PH martensitic stainless steel".

As-is characteristic An as-is characteristic is the physical manifestation or

[6] As-is represents the current value of a characteristic and is a complex combination of as-built, as-operated, as-maintained, as-repaired and as-modified. As-built characteristics are applicable only during production, and thus represent a special case of as-is. Since V&V are life cycle processes, the term as-is is often more appropriate than as-built.

ISBN 978-0-620-72719-8

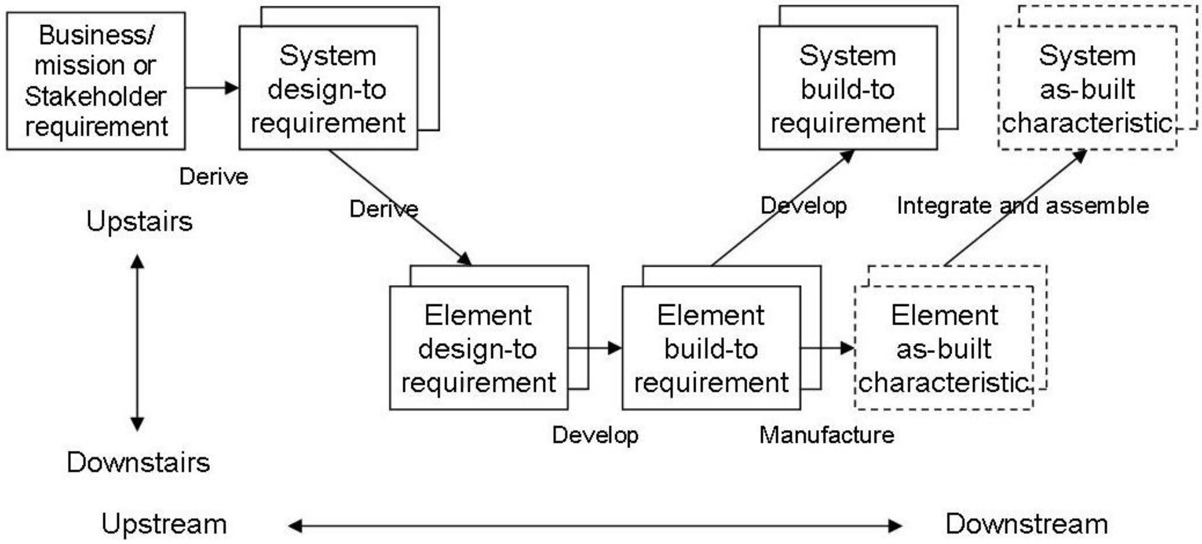

Figure 1 The Vee-model illustrating different categories of requirements and characteristics

embodiment of a build-to requirement, see Section 3. The interaction between a number of physical as-is characteristics may through emergence generate a functional as-is characteristic.

A design-to requirement cannot be manufactured. An artisan on the factory floor or on a construction site can do nothing with a list of desired functional requirements. All she can do is to implement a set of build-to requirements in the hope that each corresponding as-built characteristic will satisfy that build-to requirement. Element build-to requirements are instructions for the manufacturing process and system build-to requirements are integration and assembly instructions, each with its associated verification activities.

Figure 1 also relates these different requirements to the Vee-model [ISO/IEC 24748-2:2016], and follows the convention of naming the next-lower layer of a system an element [ISO/IEC/IEEE 15288:2015]. The principle of emergence [Checkland 1999] [Adcock 2016] states that every system exhibits emergent characteristics that derive from its elements and their interaction, but cannot be reduced to them. These emergent characteristics are meaningful only when attributed to the system, not to its elements. The principle of a hierarchy [ISO/IEC 24748-2:2016] asserts that all systems exist in a hierarchy. Each layer in a hierarchy is a system in its own right. The next-higher layer is its environment and the next-lower layer contains its elements. The principles governing one hierarchical layer also govern all other layers. Emergent properties distinguish layers. By the principle of a hierarchy, what is valid for a system is equally valid for an element; hence Figure 1 can be recursively applied at many layers.

The Vee-model is defined in terms of both time and layers. The terms “upstream” and “downstream” will be used for a traverse forwards and backwards along the system life cycle, relative to the requirement-of-interest. The terms “upstairs” and “downstairs” may be used for a traverse up and down the system hierarchy; with upstairs meaning higher-layer, and downstairs meaning lower-layer[7]. Since this distinction will seldom be needed, the terms upstream and downstream will also be used for upstairs and downstairs.

In Figure 1 the relationship between an upstream design-to requirement and a downstream design-to requirement is one to many. Consider for instance a mass constraint on a system that consists of many elements. The system mass constraint will clearly need to generate a mass

[7] “Higher” does not mean superior and “lower” does not mean inferior.

ISBN 978-0-620-72719-8

constraint for each one of its many elements. Similarly, one upstream design-to requirement will result in many downstream build-to requirements. Similarly, one business requirement will result in many system design-to requirements. The relationship between a physical build-to requirement and its physical as-built characteristic is usually one-to-one.

A design-to requirement is not converted or transformed to a build-to requirement and then just disappears—each remains a separate requirement in its own right. Similarly, a build-to requirement is not converted or transformed into an as-built characteristic and then just disappears—each remains a separate requirement or characteristic in its own right. A requirement remains forever, to be fulfilled by an as-built characteristic until the end of the requirement's life cycle.

5 What is Validation and Verification?

The 1968 NATO conference [Naur, 1968] that coined the term software engineering did not address validation and verification itself, and the military standard on software development published in 1978 used the terms in a generic sense only [MIL-STD-1679:1978]. However, the original idea behind V&V was clear from its earliest formal definition [FIPS Pub-101:1983]: "The basic objectives in verification and validation of software requirements and design specifications are to identify and resolve software problems and high-risk issues early in the software life cycle." It has been shown repeatedly that most system problems originate from poor requirements. Requirement errors found late in the system life cycle are much more expensive to fix than those found earlier in the system life cycle, for instance during the requirements definition process [INCOSE SEH:2015].

The current definitions of verification and validation are [ISO 9000:2015[8]] [ISO/IEC/IEEE 15288:2015]:

Validation Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.

Verification Confirmation, through the provision of objective evidence, that specified requirements have been fulfilled.

V&V are in essence confidence-building exercises, since confirm means the removal of doubt by an authoritative statement or indisputable fact [Merriam-Webster 2016]. Confirmation, as used in these definitions, has an all-or-nothing binary verdict—either confirmed or not confirmed.

The V&V definitions originated in software engineering but have evolved considerably over the past thirty years. Table I summarizes how various standards define validation and verification, how those definitions differ from one standard to the other, and how those definitions have evolved. The term verification was commonly used long before the term validation was introduced [MIL-STD-109A:1961]; see the first entry in Table I. Note 1 to Table I states that the column entries are somewhat subjective, which illustrates the confusion surrounding V&V.

An important observation on Table I is that most definitions distinguish validation (has a business problem been solved?) from verification (have system requirements been satisfied?); with the most recent exception IEEE Std-1012. All definitions agree that it is always a requirement that needs to be validated or verified. All definitions agree that V&V are processes within the system life cycle, and are neither a stage nor a one-off activity nor an event. However, some definitions confuse V&V with conformity determination; see Section 9.

[8] ISO 8402:1986; *Quality—Vocabulary* was superseded by ISO 9000:1987; *Quality Management and Quality Assurance—Guidelines for Selection and Use*, which in turn was superseded by ISO 9000:2000. Neither ISO 8402 nor ISO 9000:1987 defined validation and verification.

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Standard		*Definition (slightly shortened)*	*Which requirement-of-interest is to be validated or verified?*				*Which artifact is to be examined to provide objective evidence of requirement-of-interest fulfillment?*			
			Bus/miss or stake-holder rqmnts	*Specified require-ments*	*Stage outputs (note 5)*	*Process outputs*	*Require ment-of-interest itself (Alt 1)*	*Up-stream require-ment (Alt 2)*	*Down-stream require-ments (Alt 3)*	*Charac-teristics (ie system) (Alt 3A)*
MIL-STD-109A: 1961	Va	Not defined								
	Ve	The art of reviewing, inspecting, testing, checking, auditing, or otherwise establishing and documenting whether items, processes, services, or documents conform to specified requirements.		√						√
IEEE Std-729:1983	Va	… process of evaluating software at end of software development process to ensure compliance with software requirements		√						√
	Ve	… process of determining whether or not the products of a given phase of the software development cycle fulfill the requirements established during the previous phase.			√			√		
FIPS Pub-101:1983	Va	… determine the correctness of the final software produced from a development project with respect to the user needs and require-ments. … usually accomplished by verifying each stage of the software development life cycle (Note 2)	√							√
	Ve	…demonstrate consistency, completeness, correctness of software at each stage and between each stage of the life cycle (Note 2)			√			√		
RTCA 178B: 1992	Va	The process of determining that the requirements are the correct requirements and that they are complete (Note 2)	√ ?							
	Ve	… evaluate results of a process to ensure correctness and consis-tency with respect to inputs and standards for that process (Note 2)				√		√		
EIA Std 632: 1999	Va	Requirements validation is confirmation by examination that requirements (individually and as a set) are well-formulated and usable for intended use.	√ ?				√			
	Va	End product validation: confirm by examination and provision of objective evidence that the specific intended use of a developed or purchased end product is accomplished in an intended usage environment.	√							√
	Ve	End product verification: confirm by examination and provision of objective evidence that the specified requirements to which an end product is built, coded, or assembled have been fulfilled.		√						√

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Standard		*Definition (slightly shortened)*	*Which requirement-of-interest is to be validated or verified?*				*Which artifact is to be examined to provide objective evidence of requirement-of-interest fulfillment?*			
			Bus/miss or stake-holder rqmnts	*Specified require-ments*	*Stage outputs (note 5)*	*Process outputs*	*Require ment-of-interest itself (Alt 1)*	*Up-stream require-ment (Alt 2)*	*Down-stream require-ments (Alt 3)*	*Charac-teristics (ie system) (Alt 3A)*
IEEE Std 1012: 2004/ 2012	Va	… process of providing evidence that the system … satisfies requirements allocated to it at the end of each life cycle activity; solves the right problem; and satisfies intended user needs.	√	√						√
	Ve	… process of providing objective evidence that the system conforms to requirements for all life cycle processes; satisfies standards, practices, and conventions for life cycle processes; and successfully completes each life cycle activity and satisfies all the criteria for initiating succeeding life cycle activities. Verification of interim work products is essential for proper understanding and assessment of the life cycle phase product(s).			√	√				√
ISO 9000: 2000/2005/ 2015. ISO 15288: 2002/2008/ 2015. ISO 29148: 2011. SEBoK v1.5	Va	… confirm, by providing objective evidence, that the requirements for a specific intended use or application have been fulfilled.	√							
	Ve	… confirm, by providing objective evidence, that specified requirements have been fulfilled.		√						
Notes accompanying the definitions:										
ISO 9000: 2000/ 2005/ 2015	Va	1 The term “validated” is used to designate the corresponding status. 2 The use conditions for validation can be real or simulated.								
		Added in 2015: 3 The objective evidence needed for a validation is the result of a test or other form of determination such as performing alternative calculations or reviewing documents.								
	Ve	1 The term “verified” is used to designate the corresponding status. 2 Confirmation can comprise activities such as performing alternative calculations, comparing a new design specification with a similar proven design specification, undertaking tests and demonstrations, and reviewing documents prior to issue.								
		Note 2 deleted and replaced in 2015, and Note 3 added: 2 The objective evidence needed for a verification can be the result of an inspection or of other forms of determination such as performing alternative calculations or reviewing documents. 3 The activities carried out for verification are sometimes called a qualification process.								

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Standard		Definition (slightly shortened)	*Which requirement-of-interest is to be validated or verified?*				*Which artifact is to be examined to provide objective evidence of requirement-of-interest fulfillment?*			
			Bus/miss or stake-holder rqmnts	*Specified require-ments*	*Stage outputs (note 5)*	*Process outputs*	*Require ment-of-interest itself (Alt 1)*	*Up-stream require-ment (Alt 2)*	*Down-stream require-ments (Alt 3)*	*Charac-teristics (ie system) (Alt 3A)*
ISO 15288: 2002/ 2008/ 2015. ISO 29148: 2011	Va	2002: Validation in a system life cycle context is the set of activities ensuring and gaining confidence that a system is able to accomplish its intended use, goals and objectives								
	Va	Changed in 2008 to: Validation is the set of activities ensuring and gaining confidence that a system is able to accomplish its intended use, goals and objectives (i.e., meet stakeholder requirements) in the intended operational environment								
	Va	Added to note in 2015: The right system was built								
	Ve	2002: Verification in a system life cycle context is a set of activities that compares a product of the system life cycle against the required characteristics for that product. This may include, but is not limited to, specified requirements, design description and the system itself								
	Ve	Changed in 2008 to: Verification is a set of activities that compares a system or system element against the required characteristics. This may include, but is not limited to, specified requirements, design description and the system itself								
	Ve	Added to note in 2015: The system was built right								
ISO 29148: 2011	Va	Requirements validation is confirmation by examination that requirements (individually and as a set) define the right system as intended by the stakeholders.	√					√		
	Ve	Requirements verification is confirmation by examination that a requirement is well-formulated.	√	√			√			
	Notes accompanying the definitions:									
	Va	The same as for ISO 15288: 2008								
	Ve	The same as for ISO 15288: 2008								
INCOSE RWG-2015	Va	Requirement validation confirms the requirement is an agreed-to transformation that clearly communicates the stakeholder needs and expectations in a language understood by developers. The focus is on the message the requirement is communicating.	√					√		
	Ve	Requirement verification is the process ensuring the requirement meets rules and characteristics defined for writing a good requirement. The focus is on the wording and structure of the requirement in accordance with the organization's standards, processes.		√			√			

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Standard		*Definition (slightly shortened)*	*Which requirement-of-interest is to be validated or verified?*				*Which artifact is to be examined to provide objective evidence of requirement-of-interest fulfillment?*			
			Bus/miss or stake-holder rqmnts	*Specified require-ments*	*Stage outputs (note 5)*	*Process outputs*	*Require ment-of-interest itself (Alt 1)*	*Up-stream require-ment (Alt 2)*	*Down-stream require-ments (Alt 3)*	*Charac-teristics (ie system) (Alt 3A)*
INCOSE RWG-2015	Va	Design validation confirms the design will result in a system that meets its intended purpose and stakeholder expectations in its operational environment. The focus is on the message the design is communicating. "Did we design the right thing?" (Note 3)		√				√		
	Ve	Design verification is the process of ensuring the design meets the best design practice rules and characteristics of the organization. The focus is on the design process. Design verification also con-firms that the design is an agreed-to and correct transformation of design-to requirements. "Did we design the thing right?" (Note 3)		√			√	√		
	Va	System validation occurs after system verification ensuring the designed, built and verified system meets its intended purpose in its operational environment. The focus is on how well the com-pleted system meets stakeholder expectations. "Did we build the right thing?"	√							√
	Ve	System verification is done after design and build, making sure the designed and built system meets its requirements. The focus is on how well the built system meets the agreed-to requirement set that drove design and fabrication. "Did we build the thing right?"		√						√
	Comment accompanying the definitions:									
	In general, verification refers to the basics (structure) of the item being verified, making sure it meets requirements of the item, whether it be rules on writing well-formed requirements, standards and best practices (external or internal) on the design, or requirements on the system. Then validation goes beyond the basics (structure) to how well the item (requirements, design, system) communicates or addresses the needs of the entities involved.									

Note 1 The columns for this table were developed from the current definitions of validation and verification [ISO 9000:2015] [ISO/IEC/IEEE 15288:2015]. However, populating the columns becomes difficult for older definitions and turns out to be subjective. For instance, see EIA Std-632's definition of requirements validation: Does "usable for intended use" refer to business/mission or stakeholders requirements? Or to the usability of the requirement-of-interest itself? For instance, IEEE Std-1012's definition of verification is a catch-all statement attempting to include just about everything.

Note 2 "Correct" usually signifies free from faults, but the intended meaning in this context is defined in another standard. "Correctness is the degree to which … meets specified requirements, and meets user needs and expectations, whether specified or not" [ISO 24765:2010]. In other words, a correct requirement is a verified and validated requirement—which is a circular definition.

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Note 3 “Design” means information that defines the architecture, system elements, interfaces, and other requirements of a system [ISO 24765:2010].

Note 4 What EIA Std-632 calls requirements validation is the same as requirements verification defined by the INCOSE Requirements Working Group.

Note 5 A stage’s inputs usually equal the previous stage’s outputs; and may include specified requirements.

Table I Definitions of validation and verification from quality management standards and system engineering standards

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An overview of the entries in the columns of Table I readily shows that there is no consensus between standards, and neither is there a consistent conceptual development towards consensus. A lack of consensus on the concepts of V&V obviously weakens the foundations of V&V and suggests deficient V&V definitions. If those definitions don't clearly define what is V&V and what is not, in other words do not delineate the scope of V&V, they are of limited value. Where are the boundaries between V&V and related areas such as test and evaluation, design reviews, and configuration audits? For instance, is each test an instance of V&V? After all, if everything is V&V then nothing is.

Since the standards provide no convincing answers, reasoning from first principles is used before the research questions are formally discussed in Section 8.

6 Requirements and Characteristics are the Units of Analysis for Validation and Verification

Given a particular requirement-of-interest to be validated or verified, which artifact should be examined to provide objective evidence? ISO 15288 suggests the unit of analysis should be the as-is system. But an as-built system is the container for numerous as-is characteristics, and the system specification is the container for numerous to-be requirements. Which of those numerous requirements or characteristics needs to be examined? Neither a specification nor a system is the appropriate unit of analysis for a requirement-of-interest. The notes to the V&V definitions in ISO 9000 and in ISO 15288 are illuminating[9]. ISO 9000:2015 states in its notes to the definitions:

Validation "3 The objective evidence needed for a validation is the result of a test or other form of determination such as performing alternative calculations or reviewing documents."

Verification "2 The objective evidence needed for a verification can be the result of an inspection or of other forms of determination such as performing alternative calculations or reviewing documents."

However, in its notes ISO 15288:2015 states:

Validation "Validation is the set of activities ensuring and gaining confidence that a system is able to accomplish its intended use, goals and objectives (i.e., meet stakeholder requirements) in the intended operational environment. The right system was built."

Verification "Verification is a set of activities that compares a system or system element against the required characteristics[10]. This may include, but is not limited to, specified requirements, design description and the system itself. The system was built right."

Whilst ISO 9000 focuses on requirements, ISO 15288 concentrates on a system. ISO 15288 suggests that confirming that the as-built system satisfies the business/mission or stakeholder requirements is validation, and that confirming that the as-built system satisfies specified requirements is verification. In other words, the notes in ISO 15288 suggest that the V&V unit of analysis is the system itself; but ISO 9000 is silent on this matter. What is more, ISO 15288 confuses verification with conformity determination; see Section 9.

The only useful output during the concept and development stages of a system's life cycle is a set of requirements, starting from business/mission and stakeholder requirements to system design-to requirements to system build-to requirements to system as-built characteristics, see Figure 1 [INCOSE SEH:2015]. One can't wait to start with V&V until a

[9] In a standard, notes to a definition are merely intended as explanatory comments, and do not form part of the definition.

[10] Following the definition of characteristic in Section 3, the term "required characteristics" should be replaced by "requirements".

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prototype as-built system is available since that only occurs late in the development stage. If at that time it turns out that the system does not satisfy its requirements it will be too late to be of much help. During the concept and development stages the V&V unit of analysis should thus be design-to and build-to requirements since only those are available. During the production and utilization stages an as-built system will become available and the V&V unit of analysis should then be as-built characteristics. Throughout the system life cycle the most appropriate V&V unit of analysis is thus either requirements or characteristics.

7 Should Upstream or Downstream Requirements be Examined?

Should the requirement to be examined to provide objective evidence be upstream or downstream from the requirement-of-interest? To fruitfully pursue this question in all its consequences requires a detailed real-life example. Consider a portion of a vehicle breakdown structure, and a single thread of its fuel tank's design-to and build-to requirements and as-built characteristics. The numbering method is self-evident, very impractical, quite irrelevant, and merely used to refer to particular requirements. The associated verification activity for each requirement is not shown.

V Vehicle
- E Engine
- B Body
- F Fuel tank
- T Tires

Consider the following vehicle functional requirement:

Vfr1 The vehicle's unrefueled range shall be 2000 ± 100 km.

Based on the vehicle's design, the following functional design-to requirements for the next-lower layer elements have been derived. The values are reasonable but irrelevant.

- Efr1 The engine's efficiency shall be 25 ± 1%.
- Bfr1 The body's aerodynamic drag coefficient shall be 0.40 ± 0.01.
- Bfr2 The body's frontal cross section shall be 2 ± 0.15 m^2.
- Ffr1 The fuel tank's capacity shall be 180 ± 5 liters.
- Tfr1 The coefficient of rolling friction between the tires and the road shall be 0.012 ± 0.001.

Based on the fuel tank's design, the following derived physical build-to requirements have been obtained.

- Fpr2 The fuel tank shall be manufactured from a six-layered high-density polyethylene wall, with an ethylene-vinyl alcohol barrier layer in the middle.
- Fpr3 The fuel tank's wall thickness shall be 7.5 ± 0.5 mm.
- Fpr4 The fuel tank's dimensions shall be as specified in drawing 129-357 rev 1.5.

After manufacture, it turns out that the fuel tank's physical as-built characteristics are:

- Fpc2 The fuel tank consists of a six-layered high-density polyethylene wall, with an ethylene-vinyl alcohol barrier layer in the middle.
- Fpc3 The thickness of the fuel tank's wall is 7.2 mm.
- Fpc4 The fuel tank's dimensions conform to drawing 129-357 rev 1.5.

The trace relationships between these requirements and characteristics are schematically shown in Table II, with the requirement-of-interest Ffr1 shown in bold. The requirement-of-interest Ffr1 has an upstream requirement Vfr1 and three downstream requirements Fpr2, Fpr3

[11] Since Ffr1 is a specified requirement, not a business/mission requirement, verification is applicable. However, for a business/mission requirement, validation would follow precisely the same argument, except that Alternative 2 would not exist.

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and Fpr4. The fuel tank requirement thread clearly demonstrates a one-to-many relationship between vehicle functional requirement Vfr1, and the derived functional requirements for its lower-layer elements: Efr1, Bfr1, Bfr2, Ffr1 and Tfr1; see Section 4.

Consider the requirement-of-interest Ffr1: The fuel tank's capacity shall be 180 ± 5 liters. What precisely would it mean if Ffr1 were verified[11]? There are four alternative verification interpretations depending on whether the requirement to be examined to provide objective evidence, in other words the unit of analysis, is upstream or downstream from the requirement-of-interest; illustrated in Figure 2:

Functional design-to requirement	*Functional design-to requirement*	*Physical build-to requirement*	*Physical as-built characteristic*
Vehicle Vfr1	Engine Efr1	…	…
	Body Bfr1	…	…
	Body Bfr2	…	…
	Fuel tank **Ffr1**	Fpr1	Fpc1
		Fpr2	Fpc2
		Fpr3	Fpc3
	Tires Tfr1	…	…

Table II Thread of a fuel tank's design-to requirements, build-to requirements and as-built characteristics, with the requirement-of-interest shown in bold

Alternative 1 If the requirement-of-interest Ffr1 satisfies all the requirements for a requirement, in other words it is a well-formed requirement, then Ffr1 has been verified. In this approach verification concerns only the requirement-of-interest itself. In other words, if "The fuel tank's capacity shall be 180 ± 5 liters" is well-formed, then the fuel tank's capacity has been verified.

Alternative 2 If the upstream requirement Vfr1 is fulfilled when Ffr1 is satisfied, then

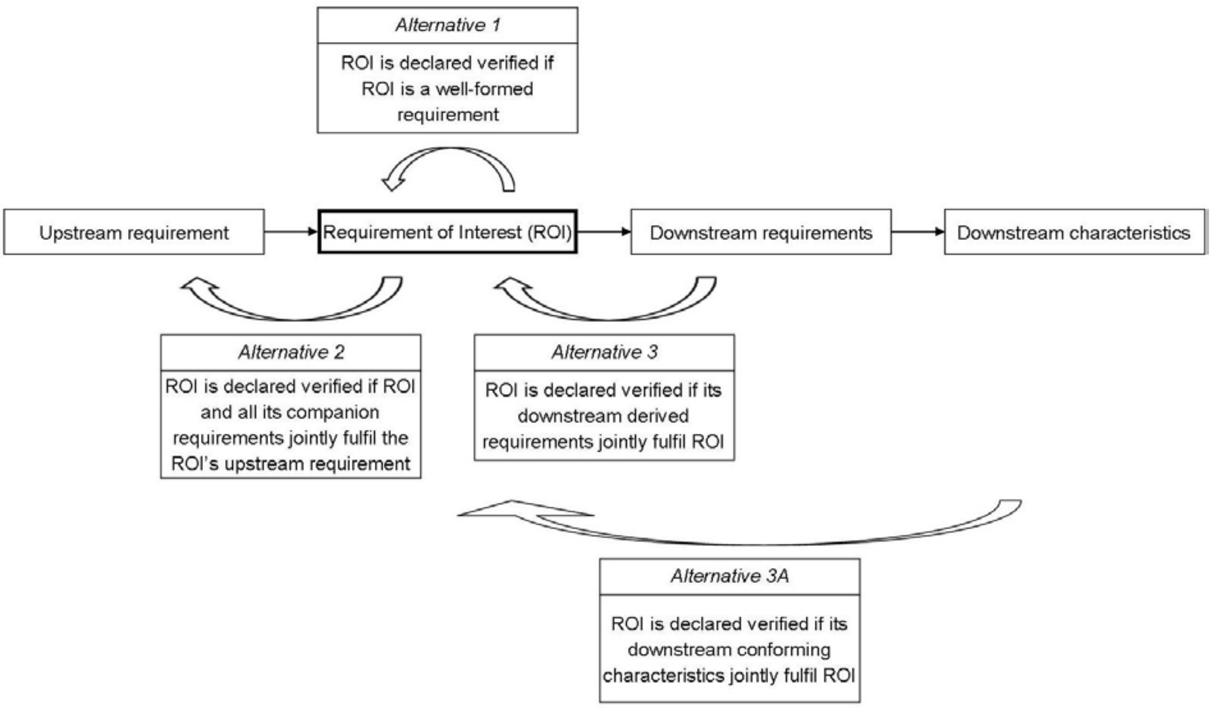

Figure 2 Upstream and downstream requirements from a requirement-of-interest

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the requirement-of-interest Ffr1 has been verified. In other words, if the vehicle has an unrefueled range of 2000 ± 100 km when the fuel tank's capacity is 180 ± 5 liters, then the fuel tank's capacity has been verified. However, this is meaningless, since a single upstream requirement Vfr1 spawns many derived requirements Efr1, Bfr1, Bfr2, Ffr1 and Tfr1, and it is their emergent property that satisfies Vfr1. Hence Alternative 2 needs to be restated: If the upstream requirement Vfr1 is fulfilled when Ffr1 and all companion derived requirements Efr1, Bfr1, Bfr2 and Tfr1 are satisfied, then the requirement-of-interest Ffr1 has been verified. In this approach verification means the requirement-of-interest as well as all its other companion derived requirements jointly satisfy their upstream requirement. In other words, if the vehicle would have an unrefueled range of 2000 ± 100 km when the engine efficiency were 25 ± 1%, and the body's aerodynamic drag coefficient were 0.40 ± 0.01 and the body's frontal cross section were 2 ± 0.15 m^2 and the fuel tank's capacity were 180 ± 5 liters and the coefficient of rolling friction between the tires and the road were 0.012 ± 0.001, then the fuel tank's capacity has been verified.

Alternative 3 If Ffr1 is fulfilled when its downstream derived requirements Fpr2, Fpr3 and Fpr4 are satisfied, then the requirement-of-interest Ffr1 has been verified. In this approach verification means that all downstream derived requirements jointly satisfy the requirement-of-interest. In other words, if the fuel tank would have a capacity of 180 ± 5 liters if the fuel tank were manufactured from a six-layered high-density polyethylene wall with an ethylene-vinyl alcohol barrier, and if the fuel tank's wall thickness were 7.5 ± 0.5 mm, and if the fuel tank dimensions were as specified in drawing 129-357 rev 1.5, then the fuel tank's capacity has been verified.

Alternative 3A If Ffr1 is fulfilled when its the downstream characteristics Fpc2, Fpc3 and Fpc4 are satisfied, then the requirement-of-interest Ffr1 is verified. In this approach verification means that all downstream conforming characteristics jointly satisfy the requirement-of-interest. In other words, if the fuel tank has a capacity of 180 ± 5 liters given that the fuel tank has been manufactured from a six-layered high-density polyethylene wall with an ethylene-vinyl alcohol barrier, and the fuel tank's wall thickness is 7.2 mm, and the fuel tank dimensions are as specified in drawing 129-357 rev 1.5, then the fuel tank's capacity has been verified.

Alternative 3A is merely a variant of Alternative 3, since Alternative 3 is based on a postulated build-to situation but Alternative 3A on an existing as-built situation. Alternative 3 occurs during the downleg and the bottom of the Vee-model, and alternative 3A occurs during the upleg; see Figure 1. The columns in Table I reflect these four V&V interpretations and Figure 2 illustrates them.

Which of these alternative verification interpretations is correct? The three alternatives are fundamentally different, hence only one should be selected. Given the definitions of V&V, it would be wrong to use one alternative in one situation and another in a different situation. As an example of such muddled thinking, some mistakenly believe that when downstream requirements are confirmed to fulfill a requirement-of-interest, it is verification; but when that same requirement-of-interest fulfills an upstream requirement, it is validation. That is inconsistent.

The logic underlying Alternative 1 is weak, since by definition if Ffr1 is a requirement, then it will be well-formed and satisfy all the requirements for a requirement [ISO/IEC/IEEE 29148:2011 clause 5.2.5]. Only requirements can be verified, not intentions. Confirming that a requirement-of-interest has been fulfilled is clearly not the same as confirming that the requirements for a requirement-of-interest have been fulfilled. However, the SE Body of Knowledge states that "To verify a stakeholder requirement or a system requirement is to check the application of syntactic and grammatical rules, and characteristics defined in the stakeholder requirements definition process, and the system requirements definition process

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such as; necessity, implementation free, unambiguous, consistent, complete, singular, feasible, traceable, and verifiable" [Adcock 2016]. Similarly, ISO 15288 states "The verification process determines the quality of the requirements with respect to the attributes and characteristics of good requirements (refer to ISO/IEC/IEEE 29148)" [ISO/IEC/IEEE 15288:2015]. Clearly, once a requirement has been defined to satisfy the requirements for a requirement [ISO/IEC/IEEE 29148:2011 clause 5.2.5] this particular definition of V&V becomes irrelevant.

The logic underlying Alternative 2 is also weak, since the requirement-of-interest Ffr1 needs to be verified jointly with its companion derived requirements Efr1, Bfr1, Bfr2 and Tfr1 by satisfying the upstream requirement Vfr1 from which they have been derived. In other words, a single verification event could jointly verify many requirements-of-interest; which does not make sense. Under Alternative 2 a single requirement-of-interest could only be verified when it has a one-to-one relationship with the upstream requirement from which it has been derived. That is an exceptional situation.

The logic underlying Alternatives 3 and 3A is sound. A compelling corroboration of its logic is that Alternative 3A is the well-established acceptance method for a product. Similarly, whilst traversing the Vee-diagram the focus of attention, and thus the requirement-of-interest, should systematically move downstream. That is precisely the basic idea in Alternative 3—after a requirement-of-interest has been verified, attention shifts to its downstream derived requirements. That does not mean upstream requirements are now ignored, but merely that the focus inevitably needs to move downstream.

The logic underlying Alternatives 1 and 2 is not inherently faulty, but it is weak. This logic might be acceptable provided it were were explicitly adopted and the alternative interpretations explicitly rejected. That has not happened since a standard needs not justify itself. On the other hand, the logic underlying Alternatives 3 and 3A is self-evident and compelling.

8 Research Results and Discussion

Research question 1 asks which requirement-of-interest is to be validated or verified. The plausible answers to this question are listed as columns in Table I, and the entries show that each possibility has been adopted by some standard. There is no consensus, and there is no consistent conceptual development or refinement towards a consensus. That justifies reasoning based on the research results and plain logic to derive sensible and informed answers to the research questions thus attempting to remove the confusion.

Once a requirement was formally defined [IEEE 729:1983], the V&V of a system or of its specification became meaningless—only requirements can be validated and verified. The V&V focus should be on a requirement-of-interest, not on a system-of-interest. After all, a system is merely the embodiment of a set of to-be requirements manifested by as-is characteristics, and its specification only the container of that set of requirements. Some accept these definitions but still disagree. For instance, [Wheatcraft 2012] states "We don't verify requirements; we verify that the system meets requirements." Similarly, the SE Handbook states that the output of verification is the "verified system" [INCOSE SEH:2015 p 92].

An unspoken assumption of most V&V definitions is that the requirement-of-interest to be validated or verified will be embodied into the to-be-developed system. However, from the earliest definitions some standards have interpreted the requirement-of-interest to be related to one of the processes in a stage in the life cycle of the to-be-developed system, in other words, the requirement-of-interest concerns an enabling system. For instance, V&V should confirm that the ISO 15288 agreement and technical management processes have been satisfied. Other definitions refer to fulfilling requirements established during the previous stage (or phase). Since the inputs to a given stage usually equal the outputs from its previous stage, typically a

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set of requirements, that is similar to the current definition of verification.

That life cycle management processes such as defined in ISO 15288 should be satisfactorily implemented is obviously true. In fact, most modern standards have processes as their building blocks. However, the concepts of processes should not be selected, named and used inadvertently, but should follow the appropriate generally-accepted international standards. In that context a careful distinction needs to be made between process performance and process capability [ISO/IEC 33000:2015].

Process performance is the extent to which the execution of a particular process achieves its purpose. A Process Reference Model, for instance ISO 15288, defines a set of life cycle processes in terms of the purpose and outcomes of each process, and is used to evaluate the performance of each process. It is self-evident, and standard management practice, that process performance should be evaluated. process outputs? On the other hand, process capability characterizes the ability of a particular process to meet business goals using a Process Assessment Model. The process capability level is measured on an ordinal scale (Incomplete process, Performed process, Managed process, Established process, Predictable process, and Optimizing process). An Organizational Maturity Model defines the extent to which an organization consistently implements a set of processes. The organizational maturity level is also measured on an ordinal scale (Immature organization, Basic organization, Managed organization, Established organization, Predictable organization, and Innovating organization). Process assessment concepts were initially defined in a family of seven process assessment standards [ISO/IEC 15504]. ISO has recently published a suite of seven second-generation process assessment standards [ISO/IEC 33000] with more in development. Those standards do *not* use the terms validation and/or verification for process assessment.

It would be folly for the systems engineering community to use the terms validation and verification for process performance and process assessment since that would needlessly confuse issues by disregarding the applicable standards.

Research question 2 asks which artifact is to be examined to provide objective evidence of requirement-of-interest fulfillment. What is the unit of analysis for a requirement-of-interest? Is it the requirement-of-interest itself? Or is it the as-built system? Or a prototype of that system? Or the requirements for that system? The definitions in Table I, and in particular the notes to some definitions, conflict with one another. The alternative units of analysis have been defined and discussed in Section 7, and are column headings in Table I.

As concluded in Section 7, the logic underlying alternatives 3 and 3A is self-evident and compelling.

Research question 3 asks which objective evidence about downstream requirements and characteristics should be provided and how it should be obtained. The definitions from Table I do not answer this question, but the notes to recent definitions suggest that analysis, inspection, demonstration, or test should be used as verification activities [ISO 9000:2015 Note 3 to Validation and notes 2 and 3 for Verification]; see Section 9.

The content analysis of the V&V definitions in quality management and in system engineering standards does not support any answer to the three research questions and leaves them open.

9 Validation and Verification of a Requirement

Given a particular requirement-of-interest, how should its downstream requirements or characteristics be examined to provide objective evidence to confirm that the requirement-of-interest has been satisfied? Precisely how should V&V be performed?

Figure 3 explains the V&V process in the context of model-centric system engineering. A model is a simplified representation of selected aspects of a system at some point in time or space to promote understanding of the real system [Adcock 2016]. Of course, a requirement

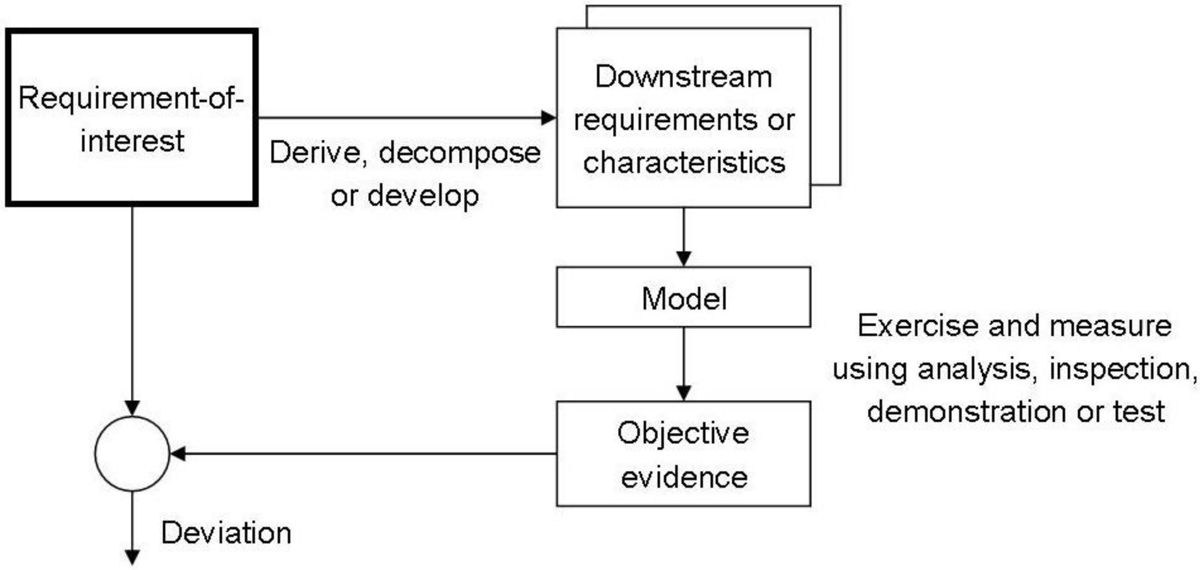

Figure 3 Validation and verification of a requirement-of interest

itself is a model of a to-be-developed system. A physical model is a concrete representation that can be felt and touched, but a functional model is a more abstract representation. All of these models may be used for V&V.

A model is constructed of all downstream requirements that were decomposed, derived or developed from the requirement-of-interest, so that the model is a representation of those downstream requirements. The model is exercised, in the sense of repeated use, its performance is measured, objective evidence is obtained and compared with the requirement-of-interest. If the objective evidence satisfies the requirement-of-interest, the requirement-of-interest has been validated or verified, and the downstream requirement can be used with confidence for further development or production. When the requirement-of-interest was manufactured resulting in a set of as-built characteristics, the measurement is a simple acceptance test to determine conformance. If the objective evidence does not satisfy the requirement-of-interest, the decompose, derive or develop activity needs to be repeated—design is an iterative process.

Since V&V depend on models, it is crucial to understand that in the modeling and simulation community the terms validation and verification have a different meaning from those discussed here [DODD 5000.59:2007] [DODI 5000.61:2009]: Validation is the process of determining the degree to which a model and its associated data is an accurate representation of the real-world from the perspective of the intended uses of the model. Verification is the process of determining that a model implementation accurately represents the developer’s conceptual description and specifications. These differences in meaning between the V&V of a requirement and the V&V of a model of that requirement, are a fertile source of confusion.

Is verification the same as conformity determination? An older definition of conformity than that in Section 2 is: A conformity is the fulfillment by an item or a service of a specified requirement [ISO 8402:1986]. In other words, validation or verification of a requirement-of-interest concerns the downstream requirements derived or developed from it; but a conformity of a characteristic-of-interest concerns the upstream requirement from which it has been manufactured. Stated differently, a requirement is validated or verified, but a characteristic is determined to be conforming or nonconforming. Once a particular characteristic is shown to be conforming, the related requirement it fulfils becomes verified. For instance, what [INCOSE RWG:2015] defines as system verification is in fact conformity determination.

ISBN 978-0-620-72719-8

[IEEE Std-1012:2012] also confuses V&V with conformity determination. That seems trivial: After all, what would be the difference in a definition of validation and verification between “the requirements have been fulfilled” and “the system has fulfilled its requirements”? If one statement were true, the other would also be true. However, “the system has fulfilled its requirements” means that the unit of analysis of a requirement-of-interest is an as-built system. By definition V&V now has to wait until an as-built system becomes available towards the end of the development stage. That is much too late and is a fatal notion for meaningful V&V. Small differences in terminology clothe major differences in concepts[12]. The definition of V&V clearly states that “requirements have been fulfilled”. Of course, once an as-is system exists, the distinction between verification and conformity determination disappears.

10 Validation and Verification Activities

Four standard validation/verification activities have been defined [INCOSE SEH:2015] [ISO/IEC/IEEE 29148:2011 clause 6.4.2.1]. Since both validation and verification are processes and all processes are defined as having at least one activity [ISO/IEC/IEEE 15288:2015 Annex D], the term V&V activity will be used rather than V&V method which is customarily used. For the sake of clarity only the term verification or verify will be used, but the discussion is equally applicable to validation or validate.

The verification activity for a requirement-of-interest specifies how the model of its downstream requirements or characteristics will be exercised and objective evidence will be obtained to confirm that the requirement-of-interest has been fulfilled. The verification acitivity is defined in the same document as the requirement-of-interest itself. Note that a requirement-of-interest’s verification activity should be specified before the downstream requirements have been derived or developed.

Analysis In analysis a functional model, for instance an allocation or derivation model, is exercised using generally-accepted scientific and technical principles, procedures and practices. A range of input values is applied to the functional model whilst it calculates or simulates an output. Analysis is typically closed-out at a design review. A typical example of analysis as a verification activity is exercising a price-elasticity-of-demand model or a tracking accuracy budget.

Inspection Inspection consists of a visual examination and superficial check of a physical model. Inspection is generally non-destructive and typically includes the use of sight, hearing, smell, touch, and taste; simple physical manipulation; mechanical and electrical gauging and measurement. A typical example of inspection as a verification activity is the inspection of as-built characteristics.

Demonstration In demonstration the functional performance of a physical model is observed without the use of instrumentation or test equipment. Observations are made and compared with predetermined responses. Only check sheets are used rather than recordings of actual performance data. A typical example of demonstration as a verification activity is the observation of reliability, maintainability, transportability, and human factor characteristics.

Test Review of test data consists of the examination and investigation of functional performance data previously collected during an instrumented test of a physical model whilst subjected to specified operating and environmental conditions using instruments other than those that are a normal part of the requirement. A typical example of test as a verification activity is a laboratory test or a flight test. *Note* Each test has a data analysis part, for instance to determine its measurement uncertainty, but that should not be confused with analysis as a separate verification activity.

[12] Consider for instance mass versus weight.

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Comment Test or demonstration cannot usually determine conformance under *all* operating and environmental conditions. Analysis then confirms that the limited set of conditions under which the requirement-of-interest has been tested or demonstrated are sufficient to ensure conformance under *all* conditions. Analysis thus extrapolates and/or interpolates test or demonstration results to a wider range of operating or environmental conditions.

Incidentally, [ISO 9000:2015] does not use the terms analysis, inspection, demonstration or test activities. However, it defines determination as “an activity to find out one or more characteristics and their characteristic values”. ISO 9000 defines three determination activities: Inspection and test are determinations to “show conformity”, and review is a “determination of the suitability, adequacy or effectiveness of an object to achieve established objectives”. The note to the definition of an object states: “Objects can be … imagined (e.g. the future state of the organization).” In other words, analysis, inspection, demonstration or test is each an instance of determination: Analysis is an instance of a review of a functional model. Inspection and test are instances of an activity performed on a physical model. Demonstration is not mentioned by ISO 9000, but is an instance of a test.

Analysis as a verification activity would typically occur when traversing the downleg of the Vee-model. Inspection, demonstration or test as a verification activity would typically occur when traversing the bottom or the upleg of the Vee-model. A qualification inspection, qualification demonstration or qualification test, see Section 11, usually occurs in the requirement’s worst-case operating and environmental conditions and in its end-of-life state, and is often destructive. Accelerated aging is often needed to obtain a realistic end-of-life state, creating additional difficulties. Some requirements can only be verified by qualification during the system’s utilization stage, for instance the safety of a chemical plant. On the other hand, an acceptance inspection, acceptance demonstration or acceptance test, see Section 11, is performed in the requirement’s nominal operating and environmental conditions and in its beginning-of-life state. If the acceptance inspection, demonstration or test were to be destructive, sampling would be used. The reason qualification is distinct from acceptance is the difficulty and expense of achieving worst-case operating and environmental conditions and the end-of-life state during acceptance. Combining qualification and acceptance is intrinsically difficult.

Both a business/mission or stakeholder requirement and a design-to requirement is usually only validated or verified by a qualification inspection, qualification demonstration or qualification test once during its life cycle. However, during production a build-to requirement generates many as-built characteristics, at least once for each manufactured system (or system element). The build-to requirement is verified by an acceptance inspection, acceptance demonstration or acceptance test of the as-built characteristics. Later during the system’s life cycle this may recur, for instance, a post-maintenance or a post-modification acceptance inspection, acceptance demonstration or acceptance test; except that as-is, rather than as-built, characteristics would be used.

The V&V activity for a requirement-of-interest is usually elaborated by a V&V description, a V&V event and a V&V verdict by means of a Requirements Verification Traceability Matrix [INCOSE SEH:2015] [ISO/IEC/IEEE 29148:2011]. The V&V description defines the details of how the V&V activity will be performed; the V&V event defines when it will occur; and the V&V verdict describes the outcome.

The V&V definitions use the term “objective” evidence. That is somewhat ambitious. Objective means not influenced by personal feelings, interpretations, or prejudice, based on facts, unbiased [Merriam-Webster 2016]. The verdict of the four standard V&V activities often rests on the opinion of one or more system engineers, and is thus subjective evidence.

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This is especially true for V&V activities during the concept and development stages of the system life cycle. Nevertheless, objective evidence remains the ideal.

11 Instances of Validation and Verification

Ten standard instances of V&V during the concept, development, production, utilization, and support stages of the system life cycle are described, more or less in the sequence they should be performed. Each instance is based on Figure 3 tailored to the particular situation. The first five V&V instances occur during the concept and development stages of the system life cycle.

Validate business/mission or stakeholder requirement (analysis) A business/mission or a stakeholder requirement needs to be validated by examining all the system design-to requirements that were decomposed or derived from it; see Figure 4. Since those system design-to requirements are functional requirements, its model will be a functional model, for instance a mathematical or simulation model. The model of those system design-to requirements will be exercised. If the objective evidence from the model fulfills the business/mission or stakeholder requirement, that business/mission or stakeholder requirement will be declared validated. The validation activity will be analysis, see Section 10, typically closed-out at a system requirements review at the end of the concept stage. This instance of validation needs to be substantively completed before the development stage can start.

Verify system design-to requirement (analysis) A system design-to requirement needs to be verified by examining all the element design-to requirements that were decomposed or derived from it; see Figure 5. Since those element design-to requirements are functional requirements, its model will be a functional model, for instance a mathematical or simulation model. The model of those element design-to requirements will be exercised. If the objective evidence from the model fulfills the system design-to requirement, that system design-to requirement will be declared verified. The verification activity will be analysis, see Section 10, typically closed-out at a system design review. This instance of verification is a key milestone during the development stage.

Verify element design-to requirement (qualification) An element design-to requirement needs to be verified by examining all the element build-to requirements that were developed from it; see Figure 6. Since those element build-to requirements are physical requirements, its model will be a physical model consisting of as-built characteristics of a prototype. (Some think that such as-built characteristics are not a model, but in fact it is a model of the to-be-manufactured element.) If the objective evidence from the as-built characteristics of the prototype fulfills the element design-to requirement, that element design-to requirement will be declared verified. The verification activities will be inspection,

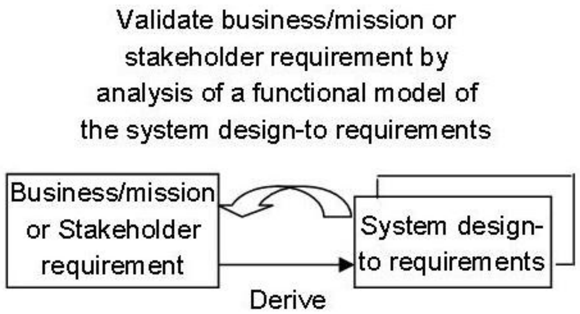

Figure 4 Validate a business/mission or a stakeholder requirement (analysis)

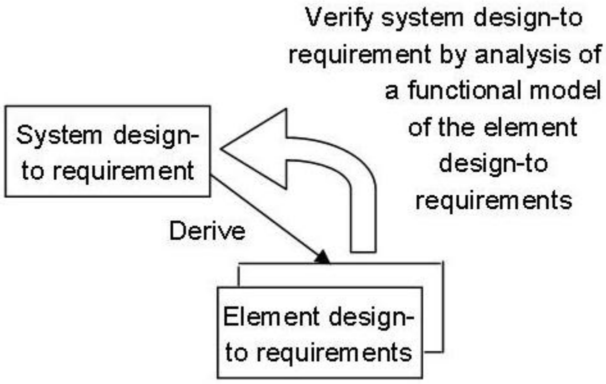

Figure 5 Verify a system design-to requirement (analysis)

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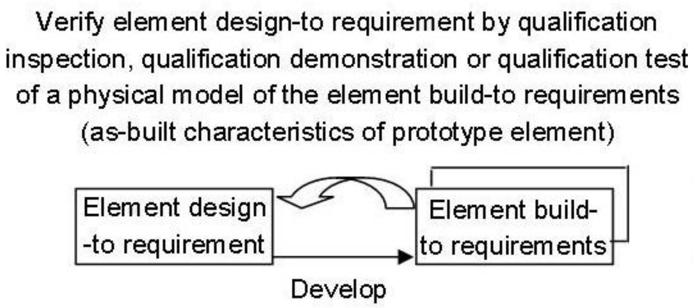

Figure 6 Verify an element design-to requirement (qualification)

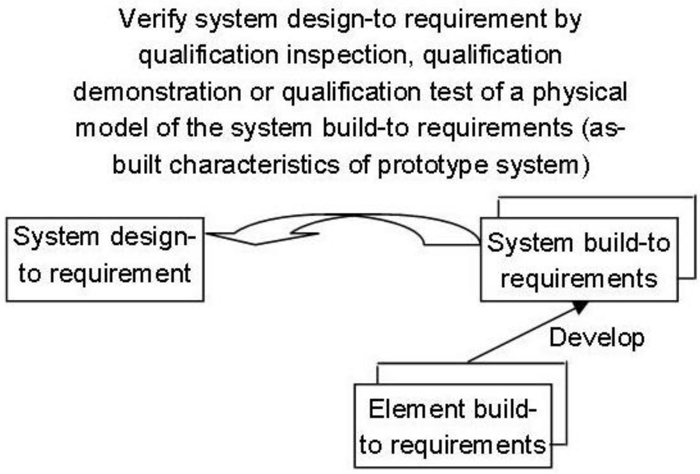

Figure 7 Verify a system design-to requirement (qualification)

demonstration and/or test, see Section 10. This instance of verification is also known as qualification, is typically closed-out at a functional and/or physical configuration audit, and is a key milestone during the development stage.

Verify system design-to requirement (qualification) A system design-to requirement needs to be verified by examining all the system build-to requirements that were decomposed or derived from it via a number of elements; see Figure 7. Since those system build-to requirements are physical requirements, its model will be a physical model consisting of the as-built characteristics of a system prototype, constructed by integrating and assembling element prototypes. If the objective evidence from that model satisfies the system design-to requirement, that system design-to requirement will be declared verified. The verification activities will be inspection, demonstration and/or test, see Section 10. This instance of verification is also known as qualification, is typically closed-out at a formal qualification review, and is a key milestone during the development stage. *Note* This qualification instance of verifying a system design-to requirement provides much more confidence than the analysis instance described above, since a physical model with its accompanying qualification inspection, qualification demonstration or qualification test is more potent than analysis of a functional model.

Validate business/mission or stakeholder requirement (qualification) A business/ mission or stakeholder requirement needs to be validated by examining all the system build-to requirements that were decomposed or derived from it; see Figure 8. Since those system build-to requirements are physical requirements, its model will be a physical model consisting of the as-built characteristics of a system prototype, constructed by integrating and assembling

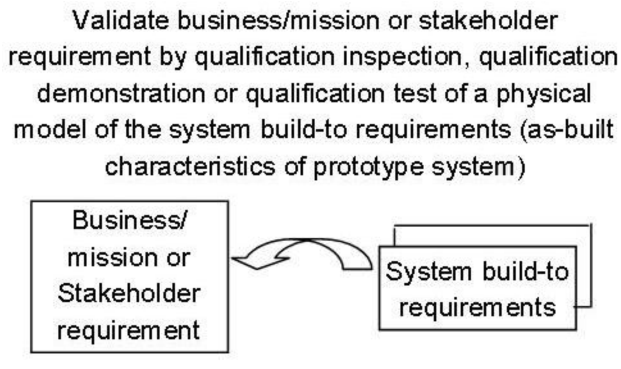

Figure 8 Validate a business/mission or a stakeholder requirement (qualification)

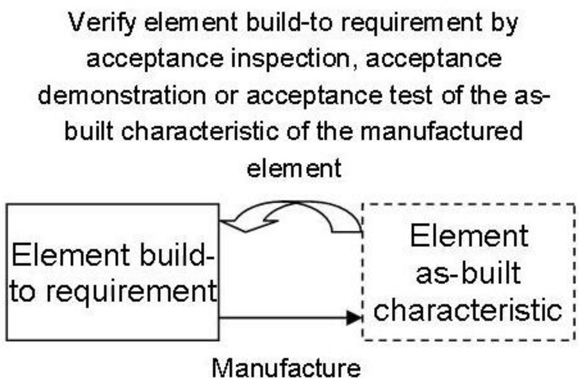

Figure 9 Verify an element build-to requirement (acceptance)

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element prototypes. If the objective evidence from that model satisfies the business/mission or stakeholder requirement, that business/mission or stakeholder requirement will be declared validated. The validation activities will be inspection, demonstration and/or test, see Section 10. This instance of validation is also known as qualification, is typically closed-out at a formal qualification review, and turns out to be the last event of the development stage. *Note* This qualification instance of validating a business/mission or stakeholder requirement provides much more confidence than the analysis instance described above, since a physical model with its accompanying qualification inspection, qualification demonstration or qualification test is more potent than analysis of a functional model.

The four V&V instances described below occur during the production stage of the system life cycle.

Verify element build-to requirement (acceptance) During the production stage a number of elements will be manufactured, each having element as-built characteristics; see Figure 9. If the element as-built characteristic satisfies its element build-to requirement, in other words the characteristic is conforming, that element build-to requirement will be declared verified. There is no need for a model. The verification activities will be acceptance inspection, acceptance demonstration or acceptance test, see Section 10.

Verify system build-to requirement (acceptance) During the production stage a number of systems will be manufactured by integrating and assembling as-built elements in accordance with the system build-to requirements; see Figure 10. If the system as-built characteristic satisfies its system build-to requirement, in other words the characteristic is conforming, that system build-to requirement will be declared verified. There is no need for a model. The verification activities will be acceptance inspection, acceptance demonstration or acceptance test, see Section 10.

Verify system design-to requirement (acceptance) It is customarily assumed that if the system as-built characteristics are conforming, then the system design-to requirements will also be satisfied. However, partial verification of system design-to requirements may be achieved by performing some qualification inspections, qualification demonstrations or qualification tests as part of acceptance, notwithstanding the intrinsic difficulties described in Section 10; see Figure 11.

Validate business/mission or stakeholder requirement (acceptance) It is customarily assumed that if the system as-built characteristics are conforming, then the business/mission and stakeholder requirements will also be satisfied. However, partial validation of business/mission or stakeholder requirements may be achieved by performing some

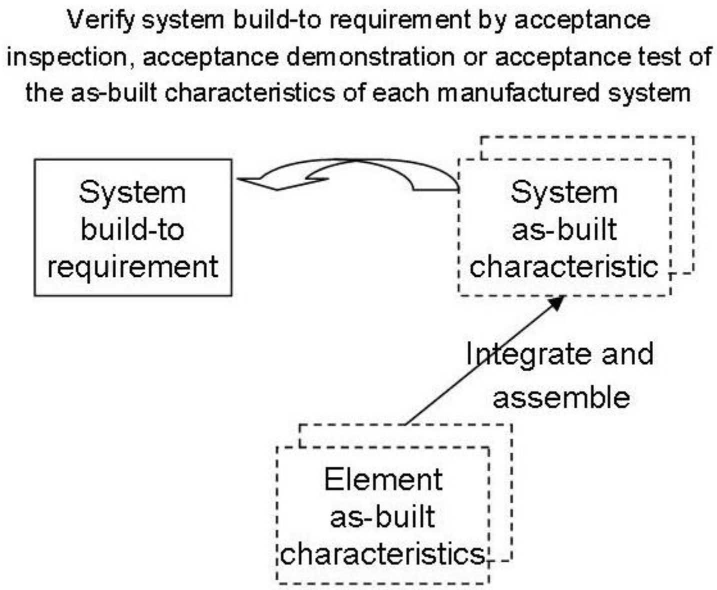

Figure 10 Verify a system build-to requirement (acceptance)

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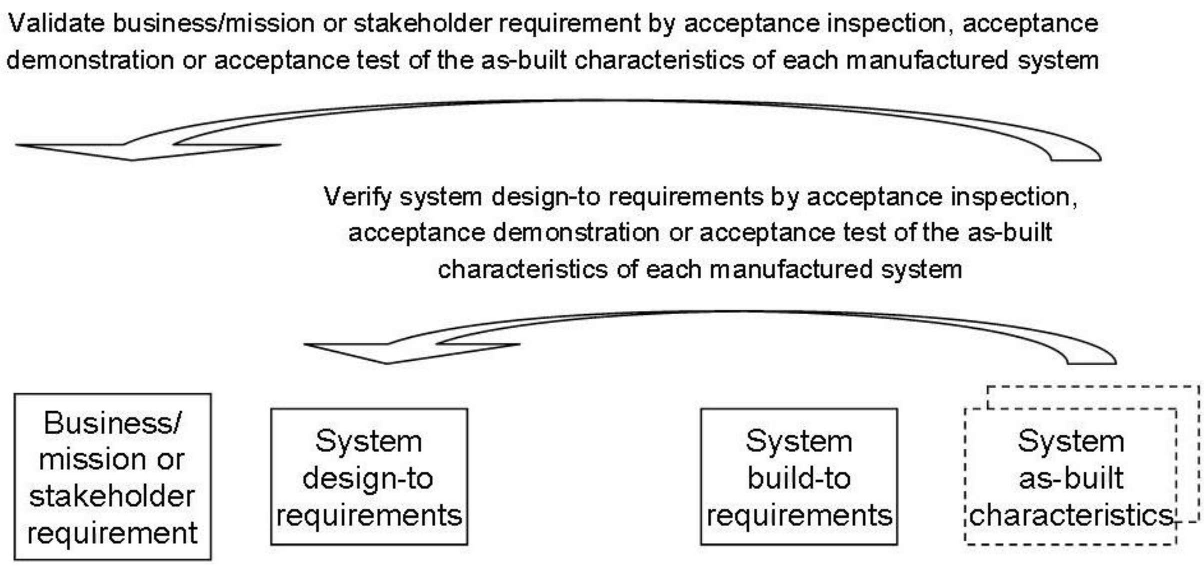

Figure 11 Verify a system design-to requirement (acceptance), and validate a business/mission or a stakeholder requirement (acceptance)

qualification inspections, qualification demonstrations or qualification tests as part of acceptance, notwithstanding the intrinsic difficulties described in Section 10; see Figure 11.

The tenth instance of V&V typically occurs during the support stage of the system life cycle.

Verify system requirement (maintenance-related) There are two categories of maintenance-related verification instances [MSG-3:2015] [S4000P:2014], see Figure 12: Firstly, verification related to corrective maintenance (repair) include diagnostic (troubleshooting) verification to identify the fault that caused the failure, and post-maintenance verification to confirm that the failure has been removed. Secondly, verification related to preventive maintenance (scheduled maintenance) include visual checks and operational checks that attempt to find hidden failures, and inspections and functional checks that attempt to detect potential failures (deterioration). Since an as-is system exists, these verification instances are equivalent to conformity determination. Since maintenance is an ISO 15288 life cycle process, these V&V instances occur throughout the life cycle.

To summarize, during the downleg of the Vee-model design-to requirements are verified by examining all those downstream design-to requirements that have been derived from it, using analysis. At the bottom of the Vee-model design-to requirements are verified by examining all those downstream requirements that have been developed from it using qualification

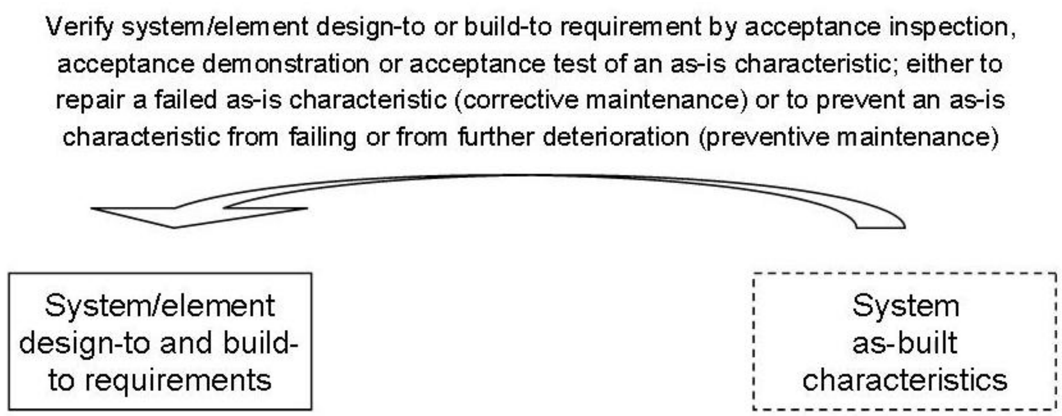

Figure 12 Verify system requirement (maintenance-related verification)

ISBN 978-0-620-72719-8

inspections, qualification demonstrations or qualification tests. During the upleg of the Vee-model a set of design-to requirements are verified again by examining all those downstream build-to requirements that have been developed from it, using qualification inspection, qualification demonstration or qualification test. During production a set of build-to requirements are verified by examining all those as-built characteristics that have been manufactured from it, using acceptance inspections, acceptance demonstrations or acceptance tests.

In general, a given requirement-of-interest is first verified by analysis during design, then verified by qualification at the end of development, verified by acceptance during production, and again verified by acceptance in later life cycle stages. After all, that is the meaning of V&V as a life cycle process. V&V activities later in the life cycle are more potent than those earlier since the model of its downstream requirements or characteristics is more realistic.

12 The Distinction between Validation and Verification

The distinction between validation and verification is rooted in the difference between a business/mission or a stakeholder requirement, and a system requirement. More specifically, the nature of a model that would provide objective evidence to confirm that a business/mission or stakeholder requirement has been fulfilled, is very different from a model that would provide objective evidence to confirm that a system design-to or build-to requirement has been fulfilled. A business requirement defines a business problem or opportunity, but system requirements specify a particular solution to that business problem. Business requirements should be ruthlessly agnostic about any particular solution, unless there are compelling reasons to the contrary. System requirements specify the best solution to that business problem, given all constraints imposed by various stakeholders. A business/mission or a stakeholder requirement is validated, and a system requirement is verified.

For instance, the business problem might be to increase a company's market share from 10% to 15% in the entertainment market segment consisting of Living Standards Measure 6 to 8 within two years. The system requirements might specify a new-generation tablet computer. Clearly the model to provide objective evidence of the future market share of a to-be-developed tablet will be completely different from a model that provides evidence that the to-be-developed tablet will for instance have internet connectivity. In other words, the model to provide objective evidence that a business problem will be solved is fundamentally different to all other models used in Section 11. There is such a fundamental difference between these models that the term validation has many years ago been selected to be different from the term verification. Nevertheless, it is debatable whether the distinction between validation and verification should be continued.

13 The INCOSE Requirements Working Group

Following [ANSI/EIA Std-632:1999], the INCOSE Requirements Working Group tried to resolve the V&V confusion as follows [INCOSE RWG:2015]:

Partition the V&V processes The V&V processes were partitioned into six subprocesses: Requirements Validation, Design Validation, System Validation, Requirements Verification, Design Verification and System Verification; see Table I. The subprocesses Requirements Validation, Design Validation, Requirements Verification and Design Verification are implicitly linked to the early stages of the system life cycle [ISO 15288:2015]. The System Validation and System Verification subprocesses are defined in terms of the late development and the production stages. Both System Validation and System Verification are defined in terms of conformity determination. Of course, since an as-is system now exists, verification is equivalent to conformity determination. Partitioning life cycle processes into

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subprocesses for a particular life cycle stage is somewhat against the spirit of a process that in principle occurs with many instances throughout the life cycle. What is more, maintenance-related V&V instances were ignored; see Section 11. This paper removes the need for subprocesses, since all are contained in the ten instances of V&V from Section11.

Expanding V&V definitions The definitions for the six subprocesses were explained as follows; see Table I [INCOSE RWG:2015]:

> In general, verification refers to the basics (structure) of the item being verified, making sure it meets requirements of the item, whether it be rules on writing well-formed requirements, standards and best practices (external or internal) on the design, or requirements on the system. Then validation goes beyond the basics (structure) to how well the item (requirements, design, system) communicates or addresses the needs of the entities involved.

This explanation is inconsistent with ISO 9000 and with ISO 15288.

14 Endorsement

A stakeholder intention cannot be validated, but nevertheless forms the anchor for the system concept stage. A business/mission or stakeholder requirement should of course be a faithful representation of the stakeholder's intention—does the stakeholder agree that the as-stated business/mission or stakeholder requirements fulfill his intentions? A confirmation process for an intention will be needed, but since an intention is not a requirement it can by definition not be validation. Since there is no word for this confirmation process, the following definition is proposed for endorsement[13]:

Endorsement Confirmation, through the provision of objective evidence, that a stakeholder's intentions have been fulfilled.

There is an argument that endorsement is a marketing process, not an engineering process. Whatever the merit of that reasoning, system engineering can contribute significantly to performing that endorsement process. Endorsement activities would be very similar to the approach from Figure 3 and the V&V activities defined in Section 10. The instance of endorsement is:

Endorse stakeholder intention (analysis) A stakeholder intention needs to be endorsed by examining the business/mission or stakeholder requirement that has been elicited from it, see Figure 13. Since that business/mission or stakeholder requirement is a functional requirement, its model will be a functional model. The model of the business/mission or stakeholder requirement will be exercised. If the objective evidence from that model fulfills the stakeholder intention, that stakeholder intention will be declared endorsed. Endorsement should occur as early as possible and is typically closed-out at a business/mission or stakeholder requirements review. *Note* In the situation of latent stakeholder intentions about to be exposed to unprecedented and disruptive technology, a stakeholder often poorly

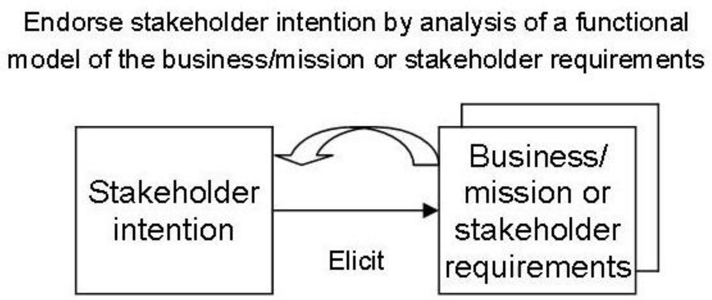

Figure 13 Endorse stakeholder intention (analysis)

[13] If Alternative 2 had been selected in Section 7, endorsement of a stakeholder intention would have been equivalent to validation of a business/mission or stakeholder requirement.

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understands an intention and finds it difficult to articulate. A healthy dose of IKIWISI (I'll know it when I see it) will be needed, based on a physical model to refine the elicited business/mission or stakeholder requirement and identify additional intentions.

Since stakeholders may come and go and their intentions are fluid, stakeholder intentions cannot be the foundation for system development—only business/mission or stakeholder requirements can be baselined to form that anchor. That is also why endorsement cannot be a formal life cycle process that is regularly repeated. Most changes to requirements do not affect upstream business/mission or stakeholder requirements and are relatively easy to disposition. However, any change to a stakeholder intention will inevitably change a business/mission or stakeholder requirement with profound downstream consequences. The anchor is thus the formal business/mission or stakeholder requirements, not stakeholder intentions.

15 A Culinary Example

Culinary technology completely illustrates V&V principles. My Italian grandmother used to bake gorgeous ciabatta bread, but always insisted on keeping her recipe secret. In her final days she relented and disclosed her recipe. After her death, we used the principle of "the proof of the pudding is in the eating". We applied the recipe, baked bread and then consumed it. As usual, the bread was delicious. But precisely what has now been confirmed: The as-baked bread? Or the bake-to recipe? Or the eater's undocumented intentions? Since the bread has been consumed and no longer exists, it is meaningless to claim that the bread has been confirmed. It is the bake-to recipe that has been confirmed. But precisely what does that mean? The first step was reading the recipe, studying the list of ingredients and relying on experience to confirm that the recipe will fulfill the eater's intentions, in other words endorsing the eater's intentions by a simple form of analysis. The second step was confirming that the as-baked bread was baked according to the recipe and that the bread thus was a reasonable model of the recipe's results. The acceptance inspection revealed that the bread was properly baked throughout and its crust had a great colour and texture, and the recipe was thus verified. The third step was eating the as-baked bread and experiencing its characteristics. The qualification demonstration confirmed that the as-baked bread satisfied the eater's intentions for healthy and delicious bread, and the eater's intentions were thus endorsed. It is not the as-baked bread that has been verified—it was merely a model of the recipe. The eater's intentions have been endorsed and the recipe has been verified. Endorsement by qualification is of course more compelling than endorsement by analysis. [Since ciabatta cannot be compared in complexity with a typical system-of-interest, no documented business/mission or stakeholder requirement exists that should be validated. Exceptionally, endorsement thus occurs a second time.]

16 Summary

The concepts of V&V are confused and confusing. A clear distinction has been made between intentions, requirements and characteristics. A content analysis of generally-accepted international standards on quality management and system engineering has been performed. Without changing the definitions from those standards, this paper has identified the issues causing confusion and in a logically-consistent way systematically resolved them. Only requirements for a to-be-developed system can be validated or verified. V&V of a requirement-of-interest occur by constructing and exercising either a functional or a physical model of all downstream requirements that were derived or developed from it, or all characteristics that were manufactured from it. Four classic verification activities—analysis, inspection, demonstration and test—define how that model will be exercised and objective evidence will be obtained to confirm that the requirement-of-interest has been fulfilled. The

ISBN 978-0-620-72719-8

ten standard instances of V&V during the concept, development, production, utilization and support stages of the system life cycle have been described. A clear distinction has been made between qualification and acceptance. Endorsement of an intention-of-interest has been defined.

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