INTEGRATIVE ENGINEERING FRAMEWORK FOR A RESEARCH AND DEVELOPMENT ENTERPRISE

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ABSTRACT

This paper proposes an Integrative Engineering Framework for performing enterprise architecture, enterprise, systems, and software engineering in a research, development, and innovation enterprise. A constructivist approach is used in developing this framework, without showing the logical predicate formalisms from philosophy of science. The framework is based on a Design Science Research process that incorporates the idea of Zachman Framework reification transformations that can integrate approaches from enterprise architecture and various engineering disciplines. The framework is also generalizable to integrate various engineering disciplines.

Keywords: Integrative Engineering Framework, Design Science Research, research, development, innovation

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1 INTRODUCTION

The global requirement for digital transformation also has an impact on the research, development, and innovation enterprise. A changing global economic landscape forces organisations to innovate new products and services faster to keep up with global competition. This requires significant effort to focus on research, development, and innovation (RDI) of new products and services for the market.

In the South African context, the need to reindustrialise domestically is seen as one of the main drivers of job creation in a country with a high unemployment rate and a low-skilled workforce. The RDI enterprise must strike a balance between RDI and supporting the industrialisation by finding alternative ways to advance for a better tomorrow for Africa by taking advantage of the opportunities that the continent has to offer [1]. This can be achieved in research grounded in science and innovation, as well as considering the needs of industry and society [1].

A framework is needed to provide innovative technologies and solutions that practically contribute to a competitive continent and sustainable economic growth [1]. The value of these technologies and solutions should be measured by determining the improvement in industry competitiveness and improving the quality of life of the people of Africa [1]. The framework should make the most of the diversity, ingenuity, and energy of African people in a collaborative and agile way to realise the potential of the continent [1].

The problem is how to strike a sensible balance between scientific and industrial research and the industrialisation of innovations, especially in an engineering organisation? The engineering organisation is understood as the Technology Development support or secondary activity, or at least part of it, in the Porter Value Chain [2].

In a discussion amongst principal engineers at a research institution in South Africa, the following outcomes, among others, have been identified for an engineering enterprise:

- Establishment and strengthening of an engineering practice based on multiple disciplines.
- Establishment and sustainment of the knowledge reference.
- Transferring of relevant knowledge to stakeholders.
- Elevated quality in activities.

For the purposes of this paper, the following disciplines are considered for integration in an engineering organisation:

- Enterprise Engineering/Architecture,
- Systems Engineering, and
- Software Engineering.

To achieve the above outcomes, the following were identified:

- Establish a generic ontology for the above engineering enterprise that can accommodate discipline-specific ontologies.
- Instil the following concepts into the culture of the above engineering organisation:
    - Enterprise Architecture / Enterprise Engineering / Enterprise Modelling.
    - Systems Engineering.
    - Software Engineering.
- Conducting scientific and industrial research as part of the engineering organisation's work every day.

- Identify and plan the research portion of the work.
- Conduct research within ethical guidelines.
- Publish research results in peer-reviewed forums; this includes formal design reviews, colloquia, patents, conferences, scientific journals, etc.

The research question answered in this paper is as follows:

> Can a framework for Enterprise Engineering/Architecture, Systems Engineering, and Software Engineering disciplines be derived to create products and services in an integrative manner in a research, development, and innovation (RDI) environment?

The derived question is:

> Can Design Science Research (DSR) be used to support an integrative approach?

The rest of this paper uses a constructivist philosophy of science approach to answer this question. The underpinning mathematical formalism for the constructs is not shown; only the interpretation of the mathematics in the context of this paper is shown. The basis for the construct, based on the research question, is discussed in the next section.

2 BACKGROUND

2.1 Architecture of the Engineering Organization

The architecture of an engineering organisation [3] is shown in Figure 1. The created system is the same as the system under development in [4]. The creating system is called the designing system in [4]. The Engineering Organisation has the main objective to develop innovative technologies and services (created system) [3] that can improve the primary activities in the Porter Value Chain so that the margin between the price of the goods and services delivered by the primary activities and the cost of delivery of these goods and services can increase [2]. This can create profits for an enterprise and, if there is competition in the market, lower prices for goods and services to the consumer [5].

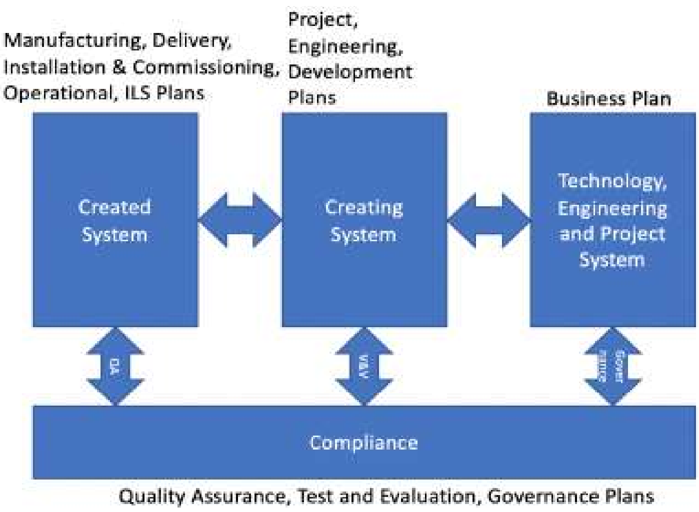

Figure 1: The Engineering Organisation [3]

The technology and services (created system) delivered by the Engineering Organisation [3] should not be confused with the goods and services delivered by the primary activities of the Porter Value Chain [2]. The created system is integrated into the larger business operations of an enterprise to support the creation of value for the stakeholders. The created system can address operational issues in the primary activities: Incoming logistics, operations, outgoing logistics, marketing and sales, and services, with the aim of increasing the margin in the value chain.

The focus of this paper is the creating system, created system and the parts of compliance that cover quality assurance (QA) of the created system as well as the verification and validation activities (V&V) of the creating system.

2.2 Design Science Research

A candidate to implement the creating system to deliver the created system with the required quality focus in an engineering organisation is to use a Design Science Research (DSR) approach [6, 7]. It has been used successfully in information systems research [7]. The experience of the authors is that DSR is implicitly performed in most engineering research work at South African universities. Engineering is the manipulation of information representing the material world (matter, energy, signals, and data [8]) to solve problems and the results are validated in the physical world [8, 9].

An expanded and revised summary of DSR in [6] is shown in Figure 2. The main activity is the creation of the artefact for an application domain, but it is based on a knowledge base. The application domain provides the requirements for the design effort (technology pull or demand pull), and the knowledge base provides the scientific grounding of the design (knowledge pull). The evaluation of the design (V&V and QA) can be done through several ways, including laboratory evaluation, field evaluation, simulation, etc. using quantitative, qualitative, or mixed-method research methods. The final testing of the solution is done in the application domain. The new knowledge gained from DSR is captured in the knowledge base (knowledge push); this includes the publication of research papers in peer reviewed forums, e.g., conference, journals, etc.

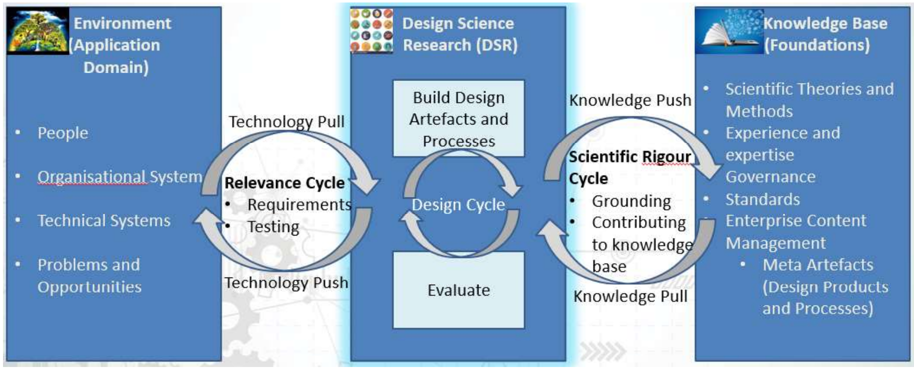

Figure 2: Summary of Design Science Research, based on [6].

The depiction in Figure 2 also includes a Technology Push, where an innovative technology is developed without requirements originating from the application domain. This is typical of technology developments following a technology readiness approach that comes from a pure theoretical basis, developed into an applicable technology to solve general problems, and later developed by technology demonstrators to mature the technology and transition it into an operational environment until it has been adopted by the market and sold commercially [10].

The phases and detailed activities of the DSR based on [7] are:

- Phase 1: Problem identification with the following activities: Identify problem, stakeholder and expert interviews, literature research - part I, pre-evaluate relevance.
- Phase 2: Solution design with activities: Design artefact, literature research - part II
- Phase 3: Evaluation with activities: Refine hypothesis, expert survey, laboratory experiment, case study/action research, stakeholder survey.
- Phase 4: Summarise results with activities: Publish research report, publish peer reviewed article, present conference paper/poster, publish engineering report, deliver engineering design, publish technical article, present design to stakeholders.

DSR provides a way in handling various technology development approaches in a research environment by keeping a balance between the problem and opportunities to be solved from the application domain and delivering a practical solution based on a foundation of peer reviewed information, i.e., scientific theories and methods, experience and expertise, corporate governance, standards, enterprise content management system, etc.

2.3 Brief overview of the Zachman Framework

This section is not an extensive overview of the Zachman Framework. Only the parts that are used in this paper are highlighted. Zachman [11] proposed a framework to deal with the increasing size and complexity of information systems implementations. It is based on a logical construct (or architecture) for defining and controlling interfaces and the integration of system components. This is done by creating a neutral descriptive framework based on various disciplines independent of information systems. The basic construct of the Zachman framework is the set product between communication interrogatives and the millennia-old reification process steps [11, 12].

The communication interrogatives are: Why, what, who, when, where and how [11, 12].

A dictionary definition of reification is "the act of changing something abstract (= existing as a thought or idea) into something real" [13]. Zachman [11, 12] identifies the steps for reification as follows:

- identification,
- definition,
- representation,
- specification,
- configuration, and
- instantiation.

In this paper, the interest is in the steps for reification.

3 CONSTRUCTING THE FRAMEWORK

3.1 Reification

For the purposes of this paper, the above reification steps above are mapped to the steps shown in Figure 3, by renaming Identification to General identification, Definition to Engineering Discipline, Representation to Meta Models, Specification to Rules and Processes, Configuration to Design, and Instantiation to Design Implementation.

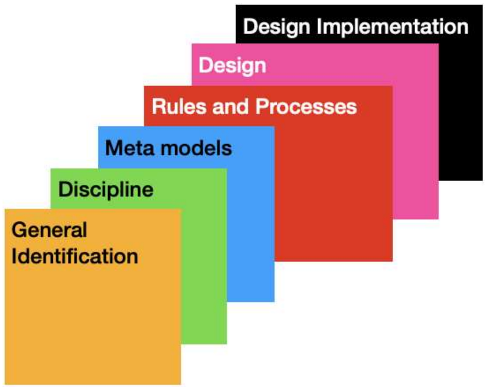

Figure 3: Reification for integrating engineering disciplines

3.1.1 General Identification

When examining the various ways in which engineering is performed in the different disciplines [14], a general engineering approach can be identified, which is shown in Figure 4. The authors also use this approach in their daily practice of engineering.

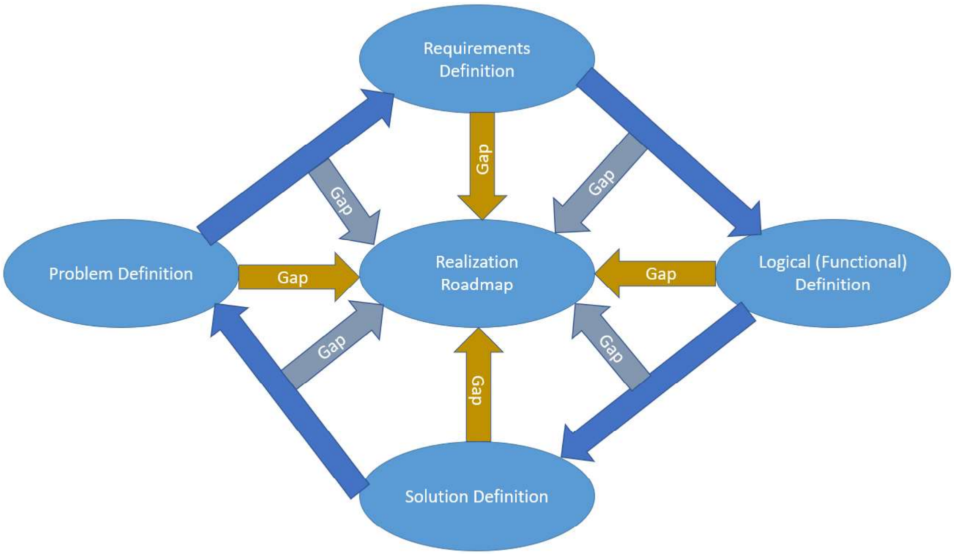

Figure 4: General Engineering Approach

This approach is widely discussed in various forms in systems engineering, software engineering, and enterprise engineering and is encoded in international standards for systems engineering and software engineering [15,16].

The General Engineering Approach in Figure 4 is the basis for relating the engineering work at a more detailed level to the DSR shown in Figure 2.

Problem definition is the starting point for any research and engineering effort. This is related to the activities in the Problem Identification Phase of the DSR.

Requirements Definition in Figure 4 is part of the cycles of relevance and scientific rigour in Figure 2. This is related to the results obtained by the activities of the Problem Identification Phase of DSR. The resulting problem definition or hypothesis is the relevant requirements evaluated through scientific rigour.

The logical/function definition in Figure 4 is part of the design and scientific rigour cycles in Figure 2. This is related to the activities of the DSR Solution Design Phase. The results are the basis for further development of the solution.

The Solution Definition in Figure 4 is part of the design and scientific rigour cycles in Figure 2. This is related to the activities of the Solution Design, Evaluation, and Summarise results phases of DSR.

The gaps indicated in Figure 4, are the information gaps that exist in an engineering approach. These gaps are the information that needs to be created to obtain a traceable design with integrity. The gaps are organised in a roadmap that is used to plan the work to be done to achieve the result. The plan is executed by the creating system and is managed by the Project Management System in Figure 1.

3.1.2 Discipline

In this transformation step, the relevant engineering disciplines that are part of the integrated development effort are identified. For the purposes of this paper, it is Enterprise Architecture, Systems Engineering, and Software Engineering. The General Engineering approach identified in the previous section allows any engineering discipline to be considered. Each discipline has its own defined set of principles and assumptions to focus on aspects of the real world.

3.1.3 Meta-Model

The information models used per engineering discipline are identified and defined to capture the information that underpins the ontology for a specific discipline. These are the models that practitioners of a specific engineering discipline use to capture their information about the materialistic world. These information models are representations of the materialistic world in which engineers solve problems.

3.1.4 Standards, Procedures, Rules, and Processes

In this transformation step, all discipline-specific rules and processes are identified to perform engineering work to solve problems. This encodes the world view of a specific discipline and how to deal with real-world problems. It is a specification of how a specific engineering discipline interprets and manipulates information representing the real world. An example is the different approaches that mechanical and chemical engineers have in solving heat transfer problems. It is the same real-world phenomenon, but each discipline uses a different approach to solving the problem.

3.1.5 Design

In this transformation step, the design information resulting from the application of rules and processes in a specific discipline is recorded. This is information on the configuration of materialistic elements (matter, energy, signals, and data) using scientific principles, and if the information is used, it will successfully instantiate machines, structures, other equipment, and systems in the real world.

3.1.6 Design Implementation

In this transformation step the instantiation of an engineering design in the real world is happening. This instantiation is based on the configuration of materialistic elements specified during the design. The real value of engineering work is only unlocked for the value chain and society after the implementation of the design.

3.2 Integrating different disciplines through cocreation and emergence

The reification process steps described above for integration can be represented as shown in Figure 5. In the forward construction process using the objects identified in each step of reification, the orange level is the General Engineering approach discussed in 3.1.1 above. For the purposes of this paper, the three green blocks in Figure 5 represent Enterprise Engineering/Architecture, Systems Engineering, and Software Engineering. The blue blocks in Figure 5 represent the metamodels for the disciplines. Each discipline can have more than one metamodel to represent information from their point of view of the real world. Each meta-model supports its own set of standard, procedures, processes, and rules.

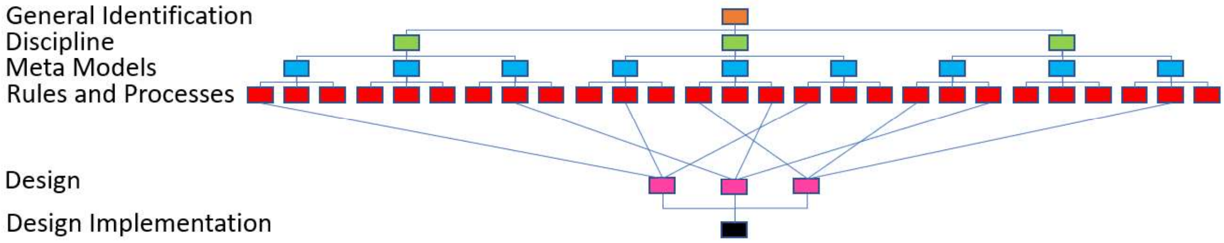

Figure 5: Illustration of the framework co-creation and emergences in design

The pink blocks in Figure 5 represent the different designs or configurations of materialistic elements according to the rules and objects that are processed. Note that a specific configuration can be influenced by more than one set of rules and processes. This represents a co-created design influenced by the applicable rules and processes sets. The implementation of this step with DSR is shown in Figure 6, with the applicable rules and processes as constraints on the process, the need (problem or opportunity of a client) as input to the process, and the design artefacts (configuration of materialistic elements) as output to the process.

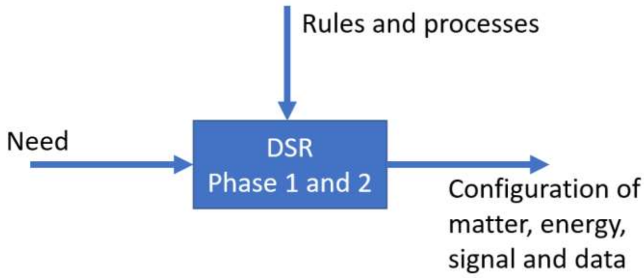

Figure 6: Realising the Design step with DSR Phases 1 and 2

The Design Implementation in Figure 7 is the instantiation of the designs in the physical world. The instantiation or realisation of designs as products or services in the real world is done by physically configuring matter, energy, signals, and data according to the design artefacts created during the design step.

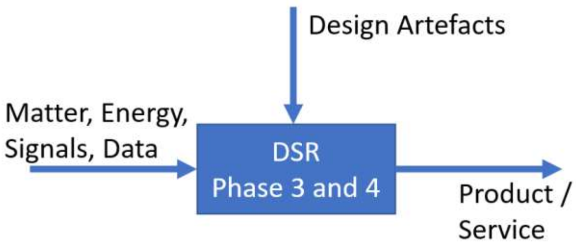

Figure 7: Realising the Design Implementation step with DSR Phases 3 and 4

The instantiation of the design in the context of DSR can be as follows:

- The minds of people, evaluated through expert and stakeholder surveys.
- A laboratory evaluated through experimentation.
- An operational environment, evaluated through case studies/action research.

The DSR phases depicted in Figures 6 and 7 are a detailed implementation of the creating system that delivers the created system in Figure 1. An important part of DSR is the publication of the results.

In the evaluation of the elements/objects from the reification transformations, a co-creation between disciplines can starting to happen when elements/objects of metamodels, rules and processes, and designs are the same. The top-down discovery of these sameness of elements leads to co-creation between disciplines on a design. When the discovery of the sameness is bottom-up, it is the emergence of the sameness of elements.

Integration between disciplines can start to happen through co-creation or emergence already during the definition of a meta-model. The primitives to describe integration and commonality are captured in the meta-model.

The rules and processes are the perspectives and interpretations of the primitives in a meta-model according to a specific discipline. For example, the primitive of a requirement and a specification exists in all engineering disciplines. The perspective and interpretation of a requirement from the perspective of Enterprise Architecture is only a need statement from the perspective of systems engineering and a motherhood statement with little meaning for implementing anything from the perspective of software engineering. These differences in perspective give rise to the observation that the specification developed by systems engineering becomes the requirements for development by discipline engineering.

3.3 Validation of the framework

The framework is validated daily in the work of the authors. It has been used in the proposals and execution of projects that require multidisciplinary integration. The first successful implementation of a tailored version of the framework was done in 2021 on a project to demonstrate augmented reality training for rock drill operators at the stope face in hard rock mines. Integration between several disciplines was planned, coordinated, implemented, and demonstrated successfully to the client by one of the authors.

The framework was also used in two proposals for research work in the research group of the authors. The one project proposal is for an underground sensor integration for advance orebody knowledge. An integrated approach between enterprise architecture, systems engineering, and software engineering could be defined with the necessary scientific rigour and practical relevance for underground hard rock mining. The other project proposal was for a system to securely facilitate online assessments of students using advanced technologies, which also required an integrated approach between enterprise engineering, systems engineering, and software engineering.

The framework provides guidance for the planning of integrated research projects to ensure scientific rigour and practical relevance while developing the artefacts for the solution. So far, only one project has been successfully delivered.

4 CONCLUSION

The construct in Section 3 is a framework that uses DSR that supports an integrative approach between different engineering disciplines using a reification process. A general engineering approach unifies the different engineering disciplines. The different engineering disciplines are supported by metamodels that contain primitives with commonality between the different disciplines and describe integration. Each discipline has a set of rules and procedures codified in standards, processes, and guidelines that are perspectives on the primitives in the meta-models. The rules and procedures control the design process for each discipline to deliver in a co-created manner design artefacts that describe the configuration of matter, energy, signals, and information. Design Implementation instantiates design artefacts in three ways: in the minds of people, in a laboratory, or in an operational environment. Also, an important part of the design implementation is publishing the results in the appropriate forums.

The framework proposed in this paper can be used to create products and services in an integrative manner in a research, development, and innovation environment facilitating the collaboration between Enterprise Engineering/Architecture, Systems Engineering, and Software Engineering disciplines.

It can be concluded that Design Science Research (DSR) can be used to support an integrative approach.

Further work following from this paper may include the full-scale development of an enterprise model using the Zachman Framework.

5 REFERENCES

[1] CSIR. 2021.*Overview presentation*, Council for Scientific and Industrial Research.

[2] Porter, M.E. 1985. *Competitive advantage: creating and sustaining superior performance*. Simon and Schuster.

[3] Erasmus, L. 2021. Architecture of the engineering organisation. *Integrating Engineering and the Human Factor eJournal*, www.uffmm.org, online: https://www.uffmm.org/2020/12/19/architecture-of-the-engineering-organisation/

[4] Long, D. and Scott, Z. 2011. *A Primer for Model-Based Systems Engineering*, 2nd Edition, Vitech Corporation.

[5] Porter, M.E. 1990. *The competitive advantage of nations*. Simon and Schuster.

[6] Hevner, A.R., March, S.T., Park, J., Ram, S. 2004. Design Science in Information Systems Research. *MIS Quarterly*, 28(1), pp 75–105.

[7] Offermann, P., Levina, O., Schönherr, M., Bub, U. 2009. Outline of a design science research process. *Proceedings of the 4th International Conference on Design Science Research in Information Systems and Technology (DESRIST '09)*. Association for Computing Machinery, New York, NY, USA, Article 7, pp 1–11.

[8] Kossiakoff, A., Sweet, W.N., Seymour, S.J., Biemer, S.M. 2011. Systems engineering principles and practice, 2nd Edition, Wiley.

[9] Pahl, G., Beitz, W., Feldhusen, J., Grote, K.H. 2007. *Engineering Design: A Systematic Approach*. 3rd Edition, Springer-Verlag.

[10] TEC-SHS. 2008. *Technology Readiness Levels Handbook for Space Applications*. 6 Edition, TEC-SHS/5551/MG/ap, European Space Agency.

[11] Zachman, J.A. 1987. A framework for information systems architecture, ***IBM Systems Journal***, 26(3), pp 276-292.

[12] Zachman, J.P. 2011. *The Zachman framework evolution*, feacinstitute.org, online: https://www.feacinstitute.org/resource/ea-articles/54-the-zachman-framework-evolution-by-john-p-zachman

[13] Cambridge. n.d. Reification. *Cambridge English Dictionary*, online: https://dictionary.cambridge.org/dictionary/english/reification

[14] Dorf, R.C. 2004. *The Engineering Handbook*. 2nd Edition, CRC Press.

[15] ISO. 2015. *ISO/IEC/IEEE 15288:2015 Systems and software engineering — System life cycle processes*, International Organization for Standardization.

[16] ISO. 2017. *ISO/IEC/IEEE 12207:2017 Systems and software engineering — Software life cycle processes*, International Organization for Standardization.