A Requirement Ontology To Guide The Analysis Of System Life Cycle Processes

Ronaldo Gutierrez

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By: Ronaldo Gutierrez

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Signed by the final examining committee:

____Chair
Dr. Catherine Mulligan

____ External Examiner
Dr. Yaoyao Fiona Zhao

____ External to Program
Dr. Ali Akgunduz

____ Examiner
Dr. Chun Wang

____ Examiner
Dr. Amin Hammad

____Thesis Supervisor
Dr. Yong Zeng

Approved by ____
Dr. Chadi Assi, Graduate Program Director

November 29, 2018 ____
Dr. Amir Asif, Dean
Gina Cody School of Engineering and Computer Science

ABSTRACT

A requirement ontology to guide the analysis of system life cycle processes

Ronaldo Gutierrez, Ph.D.
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Economies prosper by designing, manufacturing, and servicing a variety of innovative products, for example airplanes, healthcare services, infrastructure development, and information technologies. Having the right competency (aka information processing skills) for designing, manufacturing, and servicing these products is necessary for economies to exploit new opportunities. These products have become more complex to design, manufacture and serve involving people with different education, language, and possibly globally distributed. In order to create these products, information processing skills have been put to the limits causing competitiveness problems. Detailed analysis has associated these problems to requirements. Requirements involve to process different kinds of information (e.g., texts, presentations, sketches, graphs, tables, drawings, engineering analysis, and managerial analysis) during system life cycle processes (i.e., from idea generation to retirement of a product); where at each stage, information has different content (e.g., aspect, medium, and format). Therefore, a root cause associated to requirements can be attributed to a lack of a common vocabulary to communicate this variety of information in the context of system life cycle processes. Theories and models have been employed as solution to solve this communication problem; however, current practice results suggest that a more effective solution is needed. As a result, this thesis employs an ontology as a means to solve the problem which is also an alternative and complement to theories and models. In general, a requirement ontology for system life cycle processes defines the core concepts and their relationships which combined define a common vocabulary in the context of requirements for system life cycle processes. A common vocabulary enables better communication and understanding among people as a core tool to support information processing skills. Hence, an ontology as a common vocabulary is the foundation to increase competitiveness to design, manufacture, and serve a variety of innovative products; which may lead to economies prosperity.

More specifically, this thesis proposes a requirement ontology for system life cycle processes as a tool to be used to guide the analysis of these processes. Based on the fact that the ontology refers to the knowledge domain of design, guidance from a design theory (i.e., Environment-Based Design) was adopted to create the proposed ontology. Four related ontologies were created based on frequency analysis in this thesis, but the proposed core ontology contains a vocabulary of 50+2 concepts and 24 types of relationships. The proposed core ontology has been validated from different perspectives: 1) design theory (i.e., Environment-Based Design) compliance, 2) creation and evaluation from international standards (ISO 15288:2015 and ISO 29148:2011) and three European research efforts, and 3) retrospection from three case studies: a) Total Quality Management System Guideline Development Using Environment-Based Design for Area Development Planning, b) Designing the Right Framework for Healthcare Decision Support, and c) Integrating learning through design methodologies in aircraft design. This type of validation enables to speculate that the ontology can be generalized to the scope of requirements for different engineering endeavours.

At the current stage of research, the proposed ontology is an information technology product that contributes to the actual knowledge base two major aspects: 1) a common vocabulary in the context of requirements for system lifecycle processes, and 2) a replicable ontology design process that can be extended to other domains of knowledge. The current stage of the proposed ontology shall be moved forward as future research. Two major venues for future research can be considered. First, expose the proposed ontology to potential users to improve the current stage of development of the ontology. Second, use the ontology as a tool to guide the analysis of system life cycle processes (e.g., ilities or specialty engineering). The current stage of the proposed ontology and future research venues shall improve communication and understanding among people as a core tool to support information processing skills for designing, manufacturing, and servicing a variety of innovative products.

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Dedication

I dedicate my efforts and achievements

to GOD,

to my wife, *Georgia Christodoulou*

to my newborn son, *Giorgio Gutierrez*

to my parents, *Ronaldo Gutierrez Núñez & Asminia Chavarria*

to my siblings, *Roinel, Asminia, and Pedro*

and rest of family members & friends

for their unconditional support, patience, and encouragement during the past years.

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Chapter 1: Introduction

The purpose of this chapter is to introduce the problem statement, motivation/applications, objective, research contributions, and thesis organization. The problem statement (Section 1.1) describes current challenges in design practice and introduces ontologies as a solution to address the found challenges. The motivation/application (Section 1.2) states the driving force leading this research. The same section describes general applications in the domain of ontologies. The objective (Section 1.3) narrows down the scope of research by introducing the investigated research question with the corresponding formulated objective to answer the question. The research contributions (Section 1.4) define specific new knowledge generated from the investigation in this thesis. Finally, the thesis organization (Section 1.5) outlines the structure of the rest of the thesis respect to the research contributions.

1.1 Problem statement

Economies prosper by designing and manufacturing a variety of innovative products (Industry Canada, 2007, 2010, 2012; World Economic Forum, 2017, p. 319). There are challenges in designing innovative products which impede learning/teaching proper design competencies. While designing, life cycle models of systems are employed as a common reference for communication (INCOSE, 2015; ISO/IEC/IEEE, 2015). Requirements[1] are initially defined in clarifying the problem and evolve during the rest of activities in the design process (Klapsis & Thomson, 1996, 1997; Ryan, 2013). Requirements' evolution happens through the interaction of two processes: requirements development and requirements management (Bahill & Dean, 2009; W. Song, 2017; Wiesner, Peruzzini, Hauge, & Thoben, 2015, pp. 227-245). Combined these processes are known as requirements engineering (ISO/IEC/IEEE, 2011). Detailed analyses in the design of complex technical products have found challenges in these processes (Ellis-Braithwaite, Lock, Dawson, & King, 2017; Fernandes, Henriques, Silva, & Moss, 2015; Thamhain, 2013). The challenges in requirements decrease competitiveness occasioning cost overruns, delays, rework, and

[1] Requirements are product/system characteristics, conditions and constraints that are unambiguous, testable, and measurable (Ryan, Wheatcraft, Dick, & Zinni, 2015). ISO/IEC/IEEE (2011) adds a requirement is a statement translating or expressing a need and its associated constrains and conditions at different tiers in high-level form.

disregarding stakeholders' expectations (Bertoni, Bertoni, & Isaksson, 2016; Collopy, 2015; Eres, Bertoni, Kossmann, & Scanlan, 2014; Kaindl & Svetinovic, 2010; Roussel & Llorens, 2015; J. J. Y. Tan, Otto, & Wood, 2017). Therefore, the context of requirements must be analyzed systematically to discover the root causes of challenges in designing products throughout their life cycle. This discovery may facilitate learning/teaching proper design competencies.

A root cause of the challenges in designing innovative products can be initially attributed to deficiencies in teams' communication (Bloebaum & Rivas McGowan, 2012; Coso & Pritchett, 2015; Ellis-Braithwaite et al., 2017; Hallberg, Jungert, & Pilemalm, 2014; Kaindl & Svetinovic, 2010; National Research Council, 2014, pp. 1-7). Researchers in the design community have acknowledged the need to harmonize terminology employed in communication while designing products (Birkhofer, 2011; Chakrabarti & Blessing, 2016; El Kadiri & Kiritsis, 2015; Weber, 2008, 2009; Wynn & Clarkson, 2017). Nowadays, design work environments require to handle vast amounts of symbolic information and the ability to deal with the semantic context (i.e., meaning – a branch of linguistics (Colman, 2016)), where terminology plays a significant role for communication purposes (OECD, 2012, 2016). Hence, communication challenges shall be addressed to lay down the foundations to understand the big picture of problems in designing innovative products.

Two solutions have been proposed in the literature to solve the challenges in communication associated to terminology. The solutions are theories and models. Recent critical reviews of theories are presented by Chakrabarti and Blessing (2016); Weber (2009). Recent critical reviews of models are discussed by Chakrabarti and Blessing (2016); Wynn and Clarkson (2017). The review by Chakrabarti and Blessing (2016) identified the urgent need to address the challenge in terminology. The review by Wynn and Clarkson (2017) is not conclusive about the challenge indicating the difficulty to reconcile perspectives with many questions open to debate. Despite these significant reviews, it is evident that the challenge in terminology has not been effectively solved by the current solutions: theories and models.

An ontology is an alternative and complementary solution to address effectively the challenges associated to terminology and requirements in designing products (Chakrabarti & Blessing, 2016; Chandrasekaran, Josephson, & Benjamins, 1999; Hallberg et al., 2014; Kaindl & Svetinovic, 2010; Triantis & Collopy, 2014). An ontology defines the concepts and their relationships in a context of study, which is a solution to the communication challenge

(Chandrasekaran et al., 1999; Hallberg et al., 2014; Z. Li, Yang, & Ramani, 2009). Chakrabarti and Blessing (2016), and van Ruijven (2015) from the design research community argue that an ontology is considered an important basis 1) for theoretical development, and 2) in making a theory comprehensible and transferable to design practice and education. Ramadoss (2014) from the graduate students' community applied ontologies to improve healthcare systems. Hallberg et al. (2014) from the Swedish Defence Research Agency state that ontologies are effective to support collaborative activities such as systems design. Jenkins and Rouquette (2012) from NASA indicate that ontologies provide clarity in communication with benefits such as avoidance of risks and rework, which improve efficiency. Bou-Ghannam (2013) from IBM proposes the use of ontologies as the base to support the creation of smarter industries solutions. Bogusch (2015) from Airbus suggests the use of ontologies as the base to apply systems engineering. Thus, this research proposes a requirements ontology to guide the analysis of systems life cycle processes, as a foundation to increase competitiveness and succeed in the global market.

Table 1 Sample large-scale projects cost overrun (Flyvbjerg, 2014)

Project	Cost overrun (%)
Suez canal, Egypt	1,900
Scottish Parliament Building, Scotland	1,600
Sydney Opera House, Australia	1,400
Montreal Summer Olympics, Canada	1,300
Concorde Supersonic Aeroplane, UK, France	1,100
Troy and Greenfield Railroad, USA	900
Excalibur Smart Projectile, USA, Sweden	650
Canadian Firearms Registry, Canada	590
Lake Placid Winter Olympics, USA	560
Medicare transaction system, USA	560
Bank of Norway headquarters, Norway	440
Furka Base Tunnel, Switzerland	300
Verrazano Narrow Bridge, USA	280
Panama Canal, Panama	200
Montreal Metro Laval extension, Canada	160

1.2 Motivation/applications

Current design practices have been documented to lead to billion dollars cost overruns and years of schedule delays in private and public projects (Collopy & Hollingsworth, 2011; Flyvbjerg, 2014; Meier, 2008). Documented cost overruns in large projects are defined in Table 1.

Besides the cost overruns and delays in large projects, the motivation to investigate the subject in this thesis within design practices is originated based on two rationales. First, requirements affect all products. Second, there are challenges in requirements practices which hinder design competency as discussed in Section 1.1.

Considering the two rationales, the new knowledge generated through this investigation is expected to have two major implications for the industry and education communities. First, this knowledge has the potential to improve the performance of design competency. Second, this knowledge has the potential to provide the foundational concepts to create information technologies in order to support (e.g., automation) and augment (e.g., create more and better solutions with less design effort) design competency.

Considering the first implication, researchers have published about ontologies to improve the performance of design competency in industry and education. Perini, Arena, Kiritsis, and Taisch (2017) use ontologies as the foundation to create a training evaluation tool to cope with effective training needed to implement the new Industry 4.0 paradigm. van Ruijven (2015) states that ontologies have been helpful in communication during the engineering phase of several projects. Gaševic, Djuric, and Devedžic (2009, pp. 322-334) developed a set of ontologies to link learning designs and learning content to enable teachers to reuse learning designs. Zayed, Kossmann, and Odeh (2013) used ontologies to control the transfer of domain knowledge between mind maps (i.e., an effective human thinking technique) and ontologies. Mind maps support to improve conceptual skills, which is the most important for top managers beyond human and technical skills (Robbins & Coulter, 2012, p. 12). Kim, Fox, and Grüninger (1999) applied ontologies to provide shared terminology and define precise and unambiguous semantics for the enterprise in the context of quality management.

Respecting to the second implication, researchers have also published about ontologies providing foundational concepts to create information technologies to support and augment design competency. Z. Song, Sun, Wan, Huang, and Zhu (2017) suggest the use of ontologies to solve existing interoperability issues for smart e-commerce systems. El Kadiri et al. (2016) indicate the role of ontology for semantic interoperability (i.e., data integration) and for automatic reasoning capability between enterprise information systems (e.g., ERP, CRM, PDM, etc.). Panetto et al. (2016), Hinkelmann et al. (2016), and Romero and Vernadat (2016) suggest the application of ontologies to design the next generation Internet-based enterprise information systems. Chandrasegaran et al. (2013) indicate the role of ontologies for design support systems with both capabilities: 1) encoding design knowledge, and 2) facilitating semantic interoperability. X. Li, Wu, Goh, and Qiu (2018) suggest the use of ontology to support collaborative product development. The Crystal project in the European Union investigates ontologies in an industry oriented focus to increase technology readiness level in sectors such as aerospace, automotive, rail, and healthcare (Crystal, 2013a, 2013b).

Based on the potential implications out of the knowledge created in this research, it is important to formulate a specific objective for this thesis. The objective of this thesis is defined in Section 1.3.

1.3 Objective

In order to address the identified challenge in requirements while designing innovative products, this thesis investigates the research question *"what is a requirements ontology to guide the analysis of systems life cycle processes?"* Therefore, to answer the question, the objective of the thesis is *"to propose a requirements ontology to guide the analysis of systems life cycle processes"*. To achieve the objective, the research is conducted following a design approach guided by the design theory proposed by Zeng (2004b, 2011, 2015).

1.4 Research contributions

Research contributions arise while satisfying the objective of the thesis. Research contributions in this thesis are listed below:

1- Formulating the challenges associated to communicating and understanding requirements as a lack of an ontology.
2- Formulating the solution path and proposed core ontology enabled by a design theory (i.e., EBD theory).

3- Applying a step by step ontology design process that can be reused, adapted or improved for leaning purposes.
4- Defining concepts and relationships in the domain of the ontology collected from three research groups.
5- Reducing the number of concepts into minimum information models (i.e., lightest ontologies) through concept frequency analysis enabled by ISO/IEC/IEEE (2011) and ISO/IEC/IEEE (2015).
6- Integrating the reduced number of concepts and relationships into one proposed core ontology.
7- Proving that the proposed core ontology is valid with potential generalization to alternative kinds of engineering projects and services.

Table 2 Research contributions and thesis organization

Research contribution	Chapter #
1	2
2	3
3	4
4	4
5	4
6	4
7	4, 5, 6, 7

1.5 Thesis organization

The objective of the thesis leads to the research contributions in Section 1.4. Based on the research contributions, the rest of the thesis is organized into the chapters summarized in Table 2. Chapter 2 reviews critically the literature. Chapter 3 formulates the research methodology. Based on the formulated research methodology, Chapter 4 develops the ontology design process and the proposed ontology. The remaining chapters validate the proposed ontology based on retrospection on 3 case studies. Chapter 5 presents the first case study titled total quality management system guideline development using EBD for area development planning. Chapter 6 presents the second case study titled integrating learning through design methodologies in aircraft design. Chapter 7 presents the third case study titled designing the right framework for healthcare decision support. Finally, Chapter 8 concludes and outlines future work.

Chapter 2: Literature review

This review tries to address critically several arguments based on the current status of knowledge in the field of requirement, ontology, design and systems engineering. These arguments are: 1) analysis of system life cycle process is critical for system requirements analysis and modeling (Section 2.1), 2) ontology is the base for an effective and efficient analysis of system life cycle process (Section 2.2), 3) a good ontology must be sufficient and necessary to represent a targeted process, based on which existing ontology can be compared (Section 2.3), and 4) this present thesis proposes to develop the ontology following a design theory (Section 2.4). Since the arguments are related, they are intended to narrow down and rationally lead to the need of a good ontology.

2.1 Analysis of system life cycle process is critical for system requirements analysis and modeling

System requirements analysis and modeling is a complex task in terms of information processing skills[2] and people communication (Hitchins, 2007, pp. 181-312). Grady (2006, p. 7) defines that system requirements analysis is a structured, or organized, methodology for identifying an appropriate set of resources to satisfy a system need and the requirements for those resources that provide a sound basis for the design or selection of those resources. In addition, Grady indicates that the system requirements analysis acts as a transformation between the customer's system need and the design concept energized by the organized application of engineering talent. Engineering talent usually refers to multidisciplinary engineering teams (e.g., electrical, electronics, mechanical, civil, software, and engineering sciences). Multidisciplinary engineering teams generally interact with disciplines outside engineering (e.g., management, natural sciences, and social sciences) to address the needs and challenges of today's society (INCOSE, 2014, pp. 31-33; Sillitto et al., 2018). These teams decompose a statement of customer need through systematic exposition of what the system must do to satisfy that need (Grady, 2006, p. 7). The need is the

[2] In the context of design and requirements, information processing refers to analysis, synthesis, and problem solving (Eder, 2009). Eder also suggests other information processing skills such as management, decision making, and black box problem solving.

ultimate system requirement from which all other requirements[3] and the designs flow (Grady, 2006, p. 7). Modeling (aka Model-based systems engineering – MBSE), as an abstraction of reality with a common language, shall follow the whole process of system requirements analysis (Baker & Christian, 1998; Huldt & Stenius, 2018). But, MBSE is still in early stages with gaps and immaturities such as breadth & depth of system reasoning, requirement elicitation, trade-off analyses, V&V, collaboration, and management buy-in to adopt it due to lack of convincingly value propositions (i.e., elimination of rework, cycle time reduction, risk reduction, and cost reduction) in real-world problems (Madni & Sievers, 2018). Therefore, complexity puts to the limits information processing skills leading to problems in understanding and communicating breadth and depth of systems, life cycle processes, and requirements needed to apply the current vision of MBSE and solves the needs and challenges of today's society (INCOSE, 2014).

Type	#	Challenges	Reaserchers/Research groups														
			Tomiyama	Gausemeier	Wood	Paredis	Albers	Cabrera	Fenves	Adamsson	Buur	Salminen	Andreasen	Lindermann	Browning	Shea	Bradley
PRODUCT	A	Lack of common understanding of the overall system design	X	X		X	X			X		X		X	X	X	X
	B	Difficulty in assessing the consequences of choosing between two alternatives	X	X		X	X				X	X			X		X
	C	Lack of common language to represent a concept	X	X	X	X	X	X		X	X	X	X			X	X
	D	Modeling and controlling multiple relations in the product concept	X	X		X	X			X				X	X		
	E	Being in control of the multiple functional states of the product		X	X		X						X				
	F	Transfer of models and information between domains (expert group)		X	X	X	X	X	X							X	X
ACTIVITY	G	Synchronizing development activities to attain concurrent engineering		X	X			X	X				X		X		
MINDSET	H	Different tradition within the domains for how to conduct creative sessions										X					
	I	Reluctant to interact with engineers from other disciplines										X					
	J	Different mental models of the system, task and design-related phenomena	X	X		X		X		X	X	X	X		X		X
COMPETENCE	K	Lack of common language to discuss freely at creative meetings	X	X				X		X	X	X	X			X	X
	L	Education within disciplines do not call for integration in professional life									X				X		X
	M	The nature of design is different	X	X						X	X		X	X			
ORGANIZATION	N	Product complexity affects the organization complexity	X	X											X		
	O	Knowledge transfer between domains is inadequate (even in cross-disciplinary teams)	X	X				X	X			X					X
OTHERS	P	Lack of a broadly accepted methodology	X	X	X	X					X	X	X	X			
	Q	Mechatronic ownership is lacking								X		X	X				
	R	System engineers are lacking detailed information of the system										X					
	S	Complexity as a generic problem	X	X	X	X	X		X	X				X	X		X

Fig. 1 Matrix relating mechatronic challenges to researchers stating them – yellow indicates problems in communication, adapted from (Torry-Smith et al., 2013)

[3] Bahill and Dean (2009, pp. 205-206) suggest that system requirement analysis is more important than solution generation, because an elegant solution to the wrong problem is less than worthless.

Current practice of system requirements analysis and modeling is affected by poor communication and understanding of the context of requirements. The context of requirements may arise from the following statement: *"the term requirement hides a complex range of document or information types that are key technical artifacts created and used throughout the system life cycle, at all levels of system structural detail"* (Arnold & Martin, 2005). During this context, poor communication and understanding of the context of requirements is manifested from Fig. 1 to Fig. 3. Fig. 1 comes from the mechatronics engineering community (now cyber-physical systems or Internet of things) (Hehenberger et al., 2016), Fig. 2 comes from the design community trying to create theories and models, and Fig. 3 comes from the systems engineering community trying to implement Model-Based Systems Engineering (MBSE). Although the communication problems in the figures can be traced back since 2013, recent publications (e.g., Fig. 3) still emphasize and acknowledge the problem in requirements. Given the fact that requirements are created and used throughout the system life cycle that all these communities share in common, the analysis of system life cycle process is critical for system requirements analysis and modeling. Based on ISO/IEC/IEEE (2015), the term system life cycle process can be defined as *set of interrelated or interacting activities to transform inputs into outputs that evolves a complete system from conception through retirement to provide benefits to the stakeholders;* for instances refer to Fig. 4. Therefore, system life cycle processes become a common framework of reference (aka life cycle model) to improve communication and understanding of system requirement analysis and modeling (ISO/IEC/IEEE, 2015; Pinquié, Rivest, Segonds, & Véron, 2015). Having such framework of reference may lead to 1) the creation of new design tools for system requirement analysis and modeling that can complement the existing set of PLM (product life cycle management) tools (Liu, Zeng, Maletz, & Brisson, 2009; Stark, 2016) (e.g., see Fig. 5), 2) improve collaboration in multidisciplinary environments (Lee, Ma, Thimm, & Verstraeten, 2008; Mahdikhah, Messaadia, Baudry, Evans, & Louis, 2014) (e.g., see Fig. 6), 3) facilitate integration and execution of traditional requirements engineering methods (e.g., Quality Function Deployment, Design Structure Matrix or N^2, Analytical Hierarchical/Network Process, Kano model, and project management) (Blanchard & Fabrycky, 2006; Dieter & Schmidt, 2009; Kossiakoff, Sweet, Seymour, & Biemer, 2011; Pahl, Beitz, Feldhusen, & Grote, 2007; Project Management Institute, 2013; Ulrich & Eppinger, 2004), and facilitate systematic, effective, objective, and complete analysis of systems life cycle processes[4] from design problem, to requirements, to specification (ANSI/EAI, 1999; Immonen & Saaksvuori, 2008, pp. 1-5; INCOSE, 2004, pp. 154-178; 2015, pp. 211-241; ISO/IEC/IEEE, 2011; Roozenburg & Eekels, 1995, pp. 132-176; Stark, 2018).

Appendix C lists the sets of main concepts the authors in this book used or created for their theories and models. What becomes immediately apparent is the strong diversity in concepts. Looking at the theories and models this diversity can have three reasons. First, most theories and models describe different aspects of the design phenomena or describe the same phenomena at different levels of resolution. This implies that these theories and models are partial theories and models, and potentially complementary. Second, the main concepts within a theory or model are interdependent: the definition of one concept influences the definition of others. For example, the definition of conceptual stage influences the definitions of the preceding and subsequent stages. This implies that the same term(s) may represent different underlying concepts in different theories and models. Third, where a similar aspect of design is described, different theoretical origins cause differences in the concept set, the concept definitions, or the terms used for essentially the same concept.

Fig. 2 Communication challenges in the design community (Chakrabarti & Blessing, 2014, p. 14)

A key system engineering challenge is achieving effective communication among stakeholders, that is, the individuals and organizations involved in specifying, using, maintaining, deploying, designing, and testing the system. A collaborative system engineering team needs certain information in common to establish a shared context for discussion. Such information typically includes key system requirements, business/mission/operational context, usage scenarios, key external interfaces (to other systems and people), high-level architecture, and key technical performance measures. In large organizations, maintaining a shared context is especially important for meaningful collaboration.

... Once again, the key problem in conducting this activity is that stakeholders seldom share a common vocabulary. This deficiency makes it difficult for them to express and explain their needs. Unsurprisingly, they resort to informal approaches to represent needs. These approaches invariably take the form of text documents accompanied by informal block diagrams. The latter tend to have incompatible and inconsistent semantics. As a result, it becomes infeasible to check them for correctness or ensure unambiguous statement of needs.

Fig. 3 Communication challenges in the systems engineering community (Madni & Sievers, 2018)

[4] Methods to guide this analysis have been previously investigated at the Design Lab, for instance refer to Z. Chen (2006), M. Chen (2006), Z. Chen and Zeng (2006), Z. Chen, Yao, Lin, Zeng, and Eberlein (2007), Wang, Zeng, Chen, and Eberlein (2013), Wang and Zeng (2009), Wang (2013) and Wan, Cheong, Li, Zeng, and Lorio (2016); therefore, the focus of this thesis is in the ontology itself, which in future research could be integrated to the previous methods.

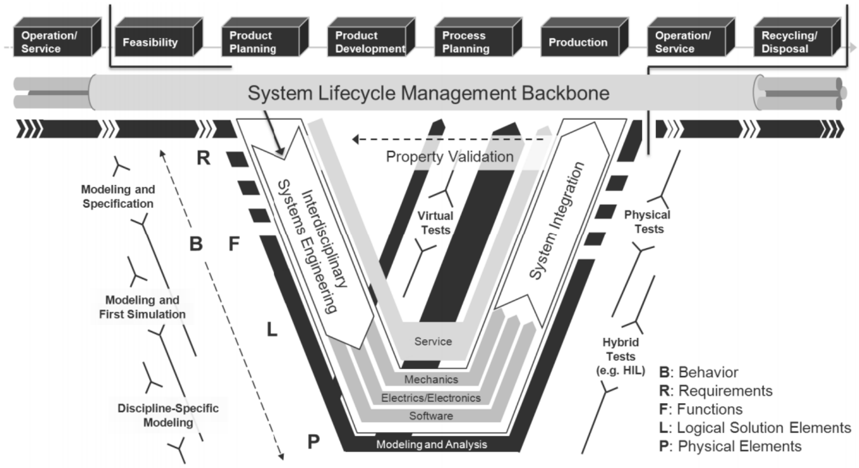


Fig. 4 Extended V-model for multi-disciplinary product development (Eigner et al., 2014)

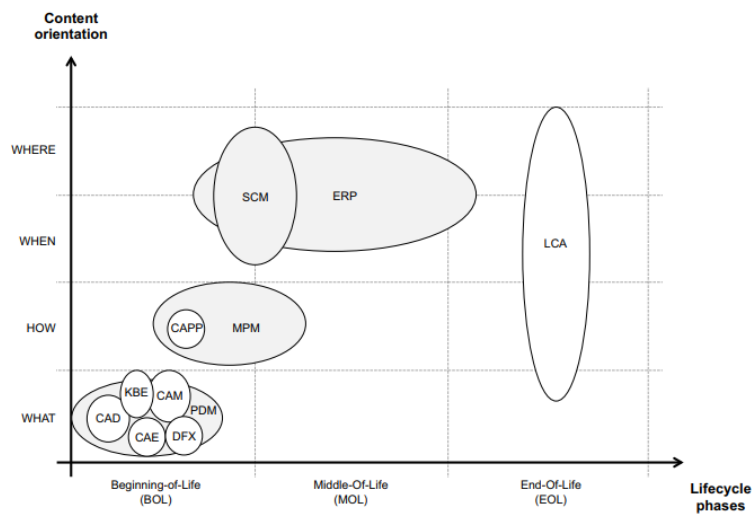


Fig. 5 Map of existing PLM systems and applications along lifecycle phases and content orientation (Demoly, Pels, & Gomes, 2013)

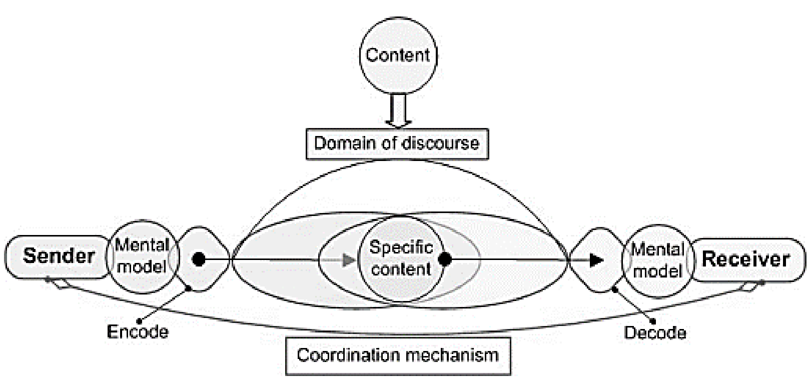


Fig. 6 A model of communication in heterogeneous environments (Toche, 2010; Toche, Huet, McSorley, & Fortin, 2010)

2.2 Ontology is the base for an effective and efficient analysis of system life cycle process

State of the art research in the area of analysis of system life cycle processes suggests that researchers focus in narrow aspects of these processes. For example, the proceedings of the 2017 model-based enterprise (MBE) summit acknowledged the gap that while lifecycle encompasses from the birth of an idea all the way to decommissioning of that idea, most of the discussion about MBE is starting in the middle of the lifecycle; therefore, there is a need to discuss more about the beginning of life cycle (e.g., stakeholder needs) (Hedberg & Carlisle, 2017, p. 5). This deficiency has also been acknowledged by Schönteich, Kasten, and Scherp (2018) who extend middle stages (i.e., engineering, manufacturing) to cover an additional lifecycle phase (i.e., the usage phase). Other related needs stated in the proceedings is the current struggle of small-to-medium enterprises (SMEs) to understand and/or gather requirements of a complete model-based workflow. In order to define a complete model-based workflow[5], Miller et al. (2017) have been working towards identifying the elements of a minimum information model (MIM) for use in a model-based definition[6]; where MIM is defined as the set of information which is required for the completion of tasks within specific phases of the product lifecycle. In general, the idea of the MIM is conceptualized in Fig. 7. Despite a survey effort covering 89 respondents, the authors conclude that to build the MIM, an ontology of engineering information would need to be created. The authors suggest that such ontology would identify the equivalent information at is passes through the lifecycle; nonetheless, the first step is to identify information used and created within each workflow. This kind of problems, i.e., difficulty in identifying the MIM, has also been manifested in large enterprises in the aerospace sector (Bernstein, Hedberg Jr, Helu, & Feeney, 2017; Quintana, Rivest, Pellerin, Venne, & Kheddouci, 2010). In this line of reasoning, this research highlights the concern that an effective and efficient analysis of system life cycle process need to be systematic, where systematic involves a holistic and connected view (big picture). From

[5] Four workflows are defined: 1) concept-to-prototype, 2) prototype-to-detailed product definition, 3) detailed product definition-to-manufacturing, and 4) manufacturing-to-inspection Miller, Hartman, Hedberg, Barnard Feeney, and Zahner (2017). Evidently, these workflows may be interpreted as fuzzy at the front-end with lack of completeness covering from inspection to retirement.

[6] MBD is a digital artifact (representation) of an object or system used to communicate information within various MBx activities in a model-based enterprise (Miller et al., 2017). The MBD shall be rich in information – shape, behavior, and context – and it travels the information architecture within an enterprise (including its extended supply chain and customers), providing input to the various authors and consumers who need it.

systematic point of view, it is acknowledged that parts work together to conform a whole (Schulz, Clausing, Fricke, & Negele, 2000; Suh, Furst, Mihalyov, & Weck, 2010; Wheatcraft, 2010); hence, a part cannot be investigated effectively and efficiently if the whole is removed from the investigated part, and the interaction (part-whole interaction) is ignored (Ahmad, Wynn, & Clarkson, 2013; Eppinger & Browning, 2012; Martin, 2000; Mueller, Dufresne, Balestrini-Robinson, & Mavris, 2011; Obergfell, Oszwald, Traub, & Sax, 2018; Pimmler & Eppinger, 1994). Investigating only parts leads to the current state of knowledge represented by silos of information with significant challenges for integrating information across the lifecycle; where such integration is needed to enable effective and efficient decision-making (Bernstein et al., 2017; El Kadiri & Kiritsis, 2015; Kulvatunyou, Wallace, Kiritsis, Smith, & Will, 2018).

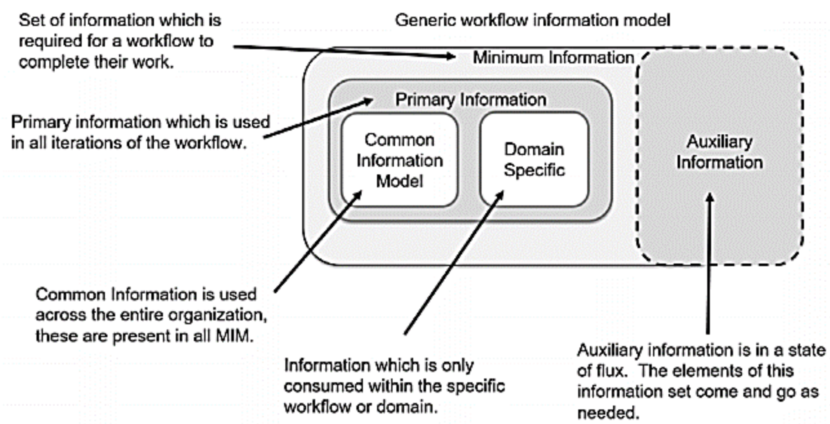


Fig. 7 MIM: primary and auxiliary information (Hartman & Zahner, 2017)

Considering the problems associated to communication and understanding either a common information model or MIM (Ruemler, Zimmerman, Hartman, Hedberg, & Barnard Feeny, 2016), ontologies are the base for an effective and efficient analysis of system life cycle processes. Effectiveness and efficient[7] analysis of system life cycle is enabled through ontologies by improving communication and understanding; for instance, refer to Fig. 8. Effectiveness and associated efficiency of ontologies to improve communication and understanding for analysis of system life cycle processes have been acknowledged in the design and systems engineering community. Design theory and models try to describe and prescribe practices for design[8]; however,

[7] Effectiveness refers to do the right thing (i.e., to communicate effectively requirements), while efficiency refers to do the right thing right (i.e., to consume the least possible resources during the effective communication of requirements).
[8] Design implies requirements and analysis of system life cycle processes.

current state of knowledge (see Fig. 9) makes explicit the need for an ontology to provide accurate descriptions of the concepts used in the framework, theories, and models proposed by the design community. The system engineering community also has developed an ontology action team as part of the INCOSE MBSE initiative (OMG, 2018 (Last modified: 2013)). This team intends to address the needs in Fig. 10. Although the ontology action team seeks the goal of machine interoperability and interpretation (reasoning) from ontologies to enable the digital thread[9], they implicitly acknowledge the need of human in the loop (i.e., stakeholders) as ontology users. Therefore, constructive efforts to create an ontology is mandatory to increase the probability of sharing and usage (Kulvatunyou et al., 2018). This fundamental effort may change the state from Fig. 6 to Fig. 11. This change may lead to new and more integrative information technology innovations besides the ones defined in Fig. 5. Hence, the change may create new opportunities for having an effective and efficient digital thread.

Effective communication requires a common vocabulary. An ontology provides a description of the terminology, concepts and relationships for a particular area of interest. An ontology may be viewed as a declarative encoding of the meaning of the domain vocabulary terms, thus making it a key to enabling communication. For systems that are used by people whose understanding of a domain is not necessarily consistent, an explicit description of the important terms can be extremely useful.

Fig. 8 An introduction to knowledge representation and ontology development for systems engineers (Kendell & Jenkins, 2010)

Although the issue of ontology was not the focus of this book, it came up in several contributions and in the discussion session. Several authors emphasised the need for an ontology to provide accurate descriptions of the concepts they used in the frameworks, theories and models they propose Agogué and Kazakçi [1], Chap. 11, Albers and Sadowsky [2], Chap. 8, Andreasen et al. [6], Chap. 9, Cavallucci [21], Chap. 12, Goel and Helms [34], Chap. 20, Gero and Kannengiesser [33], Chap. 13, and Ranjan et al. [59], Chap. 15. An ontology or—as a minimum—a clearly defined set of concepts is considered not only an important basis for theoretical development but also an important aid in analysis of empirical data and in making a theory comprehensible and transferable to design practice and education.

Fig. 9 Expression of needs for ontologies in the design community (Chakrabarti & Blessing, 2014, p. 14)

[9] The digital thread is an integrated information flow that connects all the phases of the product lifecycle using accepted authoritative data sources, e.g., requirements, system architecture, technical data package, 3D CAD models, and project tasks (Bajaj & Hedberg Jr, 2018).

Different but not necessarily compatible terminologies are used in modeling by different stakeholders. The ontologies have to be integrated to achieve semantic interoperability. Challenges in the application of ontology to large systems are that (1) the modeling of federated systems requires a broader collection of concepts and terms for which there is not yet consensus regarding their meaning, (2) the ability to take data from one lifecycle stage and repurpose it for use in later lifecycle stages, and (3) and integrating the results of models using multiple modeling languages. One of the greatest impediments in modeling a domain is the use of an incorrect ontology. An incorrect ontology is one that does not conform to the reality that it is supposed to model.

Fig. 10 Expression of needs for ontologies for systems engineering (Graves & West, 2012)

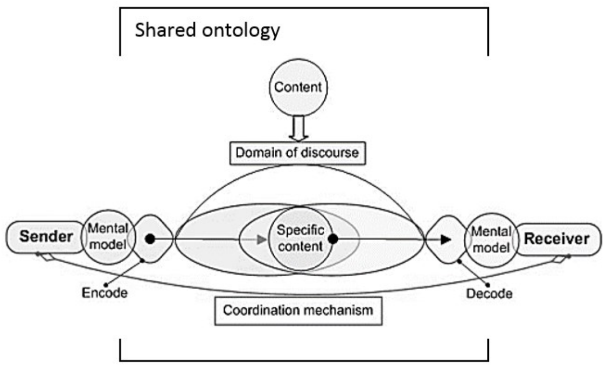


Fig. 11 Shared ontology to enable communication in heterogeneous environments, constructed based on Fig. 6

2.3 Characteristics of a good ontology

An ontology is a formal, explicit specification of a shared conceptualization (Guarino, Oberle, & Staab, 2009, pp. 2-3). A conceptualization is a body of formally represented knowledge of the objects, concepts, and other entities that are assumed to exist in some area of interest and the relationships that hold among them (Guarino et al., 2009, p. 3). So, a conceptualization defines a set called the universe of discourse and a set of relationships in the universe of discourse (Guarino et al., 2009, p. 3). The conceptualization is the investigated output in the scope of this thesis. A formal explicit specification is to employ a language to refer to the elements of a conceptualization (Guarino et al., 2009, p. 7). Levels of formality varies depending of the selected language (e.g., XML, UML, or first-order logic) (Guarino et al., 2009, p. 13). This thesis employs Recursive Object Model (ROM), which is a graphical language to handle technical English (Zeng, 2008). Based on Fig. 12, ROM can be classified as a knowledge semantic based model. For this research, ROM is considered a formal language[10], as it is based on Axiomatic Theory of Design Modeling (Zeng, 2002, 2008). In addition, propositions to translate ROM representations to other conceptual models (e.g., SysML, FBS) (Wan et al., 2016; Wang et al., 2013) and formal specifications of product requirements (Z. Chen, 2006; Z. Chen et al., 2007) have been created. Besides such positive achievements, ROM's adoption in this thesis is based on its easiness of use, understanding, and greater potential to enable communication between people (i.e., technical and non-technical stakeholders) compared to other conceptual models in Fig. 12. This rational is based on the fact that ROM represents natural language[11] such as technical English which is known and understood by all English speakers in a today's transdisciplinary design contexts (Sillitto et al., 2018). Enabling English speakers through ROM facilitates to present a shared conceptualization (Bimson & Hull, 2016). Concepts used in an ontology and their relationships shall be agreed and understood[12] by the stakeholders or potential stakeholders of the ontology in order to be a shared conceptualization (Guarino et al., 2009, p. 14). Missing to pay attention to have a shared conceptualization may lead to have useless ontologies for facilitating communication and improving understanding among stakeholders (Bimson & Hull, 2016; Guarino et al., 2009, p. 14). A shared conceptualization is made explicit in Fig. 11.

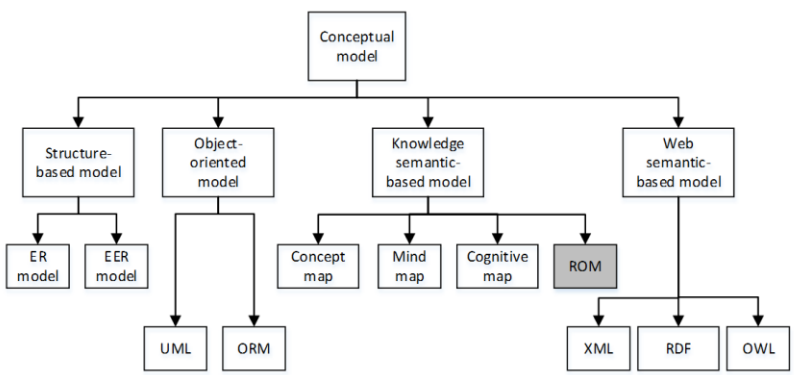


Fig. 12 Classification of the conceptual model from the functional view (Wen, Zeng, Li, & Lin, 2012)[13]

[10] Although ROM has this formality, graphical languages are sometimes classified as semiformal (Rauzy & Haskins, 2018).
[11] ROM representation of natural language is less restrictive and more expressive than traditional ontology languages such as OWL and RDF in terms of morphology, lexicon, and syntax; for instance, refer to the discussion by Bimson and Hull (2016).
[12] Agreement and understanding lead to shared conceptualization.
[13] ER stands for Entity Relationship, EER for Extending Entity Relationship, UML for Unified Modeling language, ORM for Object Role Model, ROM for Recursive Object Model, XML for Extensible Markup Language, RDF for Resource Description Framework, and OWL for Web Ontology Language.

A good ontology must be sufficient and necessary to represent a targeted process, based on which existing ontology can be compared. Based on the discussion in the previous paragraph, a good ontology is sufficient and necessary when it has a shared defined syntax (i.e., a formal, explicit specification), and a shared [associated] domain semantics (i.e., shared conceptualization of targeted process) seeking towards a MIM. Syntax comes from the modeling language employed to express the ontology (e.g., UML, SysML, or OWL). For example, a class diagram in UML and block definition diagram in SysML state the syntactical rules that define syntactically correct sentences in ontologies expressed in these languages (Graves & West, 2012). Syntactical rules are composed of two aspects: 1) rules conditions that define when the rule is valid, and 2) rules of modifications (e.g., adding, subtracting, or modifying objects) (Chakrabarti et al., 2011). Therefore, these languages (aka metamodels) determines all possible grammatically valid models in their designed domain. From computational point of view, syntactically correct ontologies enable software to check that an application model from the ontology conforms the ontology and is not just an arbitrary model (Graves & West, 2012). Automated consistency checking base on syntactically correct ontologies is of particular interest in the context of complex products (e.g., aircrafts) where manual consistency is error prone (Graves & Bijan, 2011). In a more general sense in design, syntax without any commitment to a language has been investigated as design grammar (Chakrabarti et al., 2011; Königseder, Stanković, & Shea, 2016). Despite such efforts of non-natural languages, this thesis adopts ROM[14] to represent formal, explicit specifications as it has the capabilities to handle them (Bimson & Hull, 2016; Wen et al., 2012; Zeng, 2002, 2008); but it is also easier to learn and transfer to a wider audience beyond to traditional ontology developers, software engineers, or computer scientists through the use of natural language (i.e., technical English) without creating unnecessary information overload and related stress (Workman & Riding, 2016) that can hinder productivity[15] (Adams, 2007). Syntax is used to represent semantics, but in contrast, semantics comes from domain knowledge (e.g., engineering, natural sciences, or

[14] ROM uses graphical representations sometimes called as pragmatic models. Pragmatic models opposed to pure formal models. Pragmatic models are intended primarily to support communication among stakeholders, and formal models aim primarily at calculating something (e.g., simulation) or generating something (e.g., computer code or physical object such as 3D printing, additive manufacturing) (Rauzy & Haskins, 2018).

[15] Work-related stress amounts to some 20 billion euro annually for European workers (European Commission, 1999, p. iii).

system life cycle processes) instead of a language. Semantics[16] can be represented as a set of positive statements[17] that can be interpreted as axioms in the domain of knowledge (Graves & Bijan, 2011); where the domain of knowledge of the ontology in this thesis is encompassed in two international standards: ISO/IEC/IEEE (2015) and ISO/IEC/IEEE (2011). These axioms are conformed by concepts and the relationships between them (OMG, 2010). The axioms can be proven correct if they can answer competency questions. Life cycle centered ontologies (Bruno, Antonelli, & Villa, 2015; Matsokis & Kiritsis, 2010; Schönteich et al., 2018) try to describe product life cycle management comprehensively by focusing on general concepts in contrast to engineering-centered ontologies (Foufou, Fenves, Bock, Rachuri, & Sriram, 2005; Imran & Young, 2016; Panetto, Dassisti, & Tursi, 2012) or manufacturing centered-ontologies (Imran & Young, 2016; Leitão & Restivo, 2006; Panetto et al., 2012); therefore, life cycle centered ontologies answer general competency questions such as why, what, where, when, who, and how (Wang & Zeng, 2009; Zeng, 2015). Incorrect ontology due to incorrect semantics is one of the greatest impediments to ontology use (Graves & West, 2012). Therefore, a good ontology shall deal with formal, explicit specification (i.e., syntax) of a shared conceptualization (i.e., semantics). Shared defined syntax (i.e., formal, explicit specification) and shared semantics (i.e., shared conceptualization) as core tenets to define good ontologies can also be mapped to the criteria to evaluate good ontologies suggested by Gruber (1995) and Uschold and Gruninger (1996, pp. 17-18). These authors suggest that an ontology shall deal with 5 criteria: clarity, coherence, extensibility, minimal encoding bias, and minimal ontological commitment. Each of these criteria are defined in Table 3. Based on the definitions in Table 3, criteria of a good ontology in this thesis are summarized in Table 4. Similar criteria have also been introduced and discussed by Wen et al. (2012) considering the major topics of syntax, semantics, and formality.

[16] Semantics shall not be confused with semantic operability. Semantic operability means that if two ontologies are created in SysML, they can be integrated (Graves & West, 2012). However, the resulting ontology does not necessarily shall be assumed to be semantically correct (Graves & Bijan, 2011). This assumption can lead to false conclusions.
[17] These statements have three tenets of semantics: morphology, lexicon, and conformance to selected syntax (Bimson & Hull, 2016). For this research, a good semantic is manifested in the concepts and relationships explicit in an ontology (Wen et al., 2012); i.e., the conceptualization.

Table 3 Criteria to evaluate ontologies (Uschold & Gruninger, 1996, pp. 17-18), originally from Gruber (1995)

Criteria	Definition
Clarity	An ontology shall effectively communicate the intended meaning of defined terms. Definitions shall be objective. Formalism is a means to this end. Where possible, a complete definition (a predicate defined by necessary and sufficient conditions) is preferred over a partial definition (defined by only necessary or sufficient conditions). All definitions shall be documented with natural language.
Coherence	An ontology shall be internally consistent. At least, the defining axioms shall be logical consistent. Coherence shall apply to the concepts (definitions) that are defined informally (i.e., not axiomatic) such as those described in natural language documentation and examples. If a sentence that can be inferred from the axioms contradicts a definition or example given informally, then the ontology is incoherent.
Extensibility	An ontology shall be designed to anticipate the uses of the shared vocabulary. The ontology shall offer a conceptual foundation for a range of anticipated tasks, and the representation shall be crafted so that one can extend and specialize the ontology monotonically (i.e., either entirely increasing or decreasing in a given domain). In other words, one shall be able to define new terms for special uses based on the existing vocabulary, in a way that does not require the revision of the existing definitions.
Minimal encoding bias	An ontology shall represent a conceptualization. The conceptualization shall be specified at the knowledge level without depending on a particular symbol-level encoding. The encoding bias results when representation choices (i.e., axiomatization) are made purely for the convenience of notation or implementation shall be minimized. The goal is to enable knowledge sharing across agents that may be implemented in different representation system and styles of representation.
Minimal ontological commitment	An ontology shall require the minimal ontological commitment sufficient to support the intended knowledge sharing activities. An ontology shall make as few claims as possible about the world (i.e., domain) being modelled, allowing the parties committed to the ontology freedom to specialize and instantiate the ontology as needed. Since ontological commitment is based on consistent use of vocabulary, ontological commitment can be minimized by specifying the weakest theory (allowing the most models) and defining only those terms that are essential to the communication of knowledge consistent with that theory.

Table 4 Criteria for a good ontology: necessary and sufficiency

Criteria	Syntax	Semantics	Formality
Clarity	Grammar of language (e.g., ROM) by Zeng (2008) or UML, SysML, XML, etc.	Concepts and relationships in domain of interest shall be investigated considering ISO/IEC/IEEE (2015) and ISO/IEC/IEEE (2011).	In contrast to formal mathematical languages, graphical languages such as ROM are sometimes defined as semiformal/pragmatic languages (Rauzy & Haskins, 2018). These languages are effective to express ontologies (Rousseau, Billingham, & Calvo-Amodio, 2018; Wen et al., 2012) and facilitate learning/communication (Novak & Cañas, 2008; Ruiz-Primo & Shavelson, 1996).
Coherence	ROM enables to connect naturally technical English (Zeng, 2008); hence, it enables to create consistent propositions in natural language (Bimson & Hull, 2016).	Arguments shall be created based on concepts in international standards, and other investigated research efforts.	Graphical languages with predefined syntax and construct (e.g., ROM) enables to express consistent arguments for a desired domain of discourse.
Extensibility	ROM can express technical English and handle the related variations and extensions.	ROM can handle all semantic relationships in English (NISO & ANSI, 2010, pp. 42-57).	All possible extensibility related to syntax and semantics can be handled graphically in ROM.

Minimal encoding bias	ROM can be translated to other languages, e.g., SysML (Wan et al., 2016) or conceptual models (Wang et al., 2013).	As semantics come from natural language or written technical English which is accessible to all English speakers, minimal encoding bias is expected.	ROM is composed of 5 graphical constructs (Zeng, 2008) intended to minimize graphical encoding bias.
Minimal ontological commitment	From syntax point of view, ROM proposed only 5 construct to represent graphically all part of the speech in written technical English (Zeng, 2008).	The ontology shall define a shared but only essential terms in the domain of this thesis by harmonizing the vocabulary of international standards and other ontological efforts.	ROM enables to express graphically base form of parts of the speech (e.g., nouns and verbs) which make possible future variations to specialize/instantiate these terms as needed in natural language (Bimson & Hull, 2016).

2.4 A design theory develops good ontologies

Given the current state of practice in the context of a requirement ontology to guide the analysis of systems life cycle processes, this thesis proposes to develop the ontology following a design theory. Requirements come from design, thus a design theory facilitates the representation of this context effectively. More specifically, this thesis adopts Environment-Based Design (EBD) (Zeng, 2015). During the past years, EBD has progressed from descriptive (i.e., theory) to prescriptive (i.e., methodology) (Zeng, 2011). The current state of development of the methodology has led to the creation of activities (e.g., environment analysis, conflict identification, and solution generation) and tools (e.g., ROM) to handle semantics originating in the design process intended to guide a life cycle perspective (Zeng, 2015). Therefore, the methodology is the right fit to represent the context of a requirement ontology to guide the analysis of systems life cycle processes; which satisfies the conditions in Table 4.

Chapter 3: Research methodology - an EBD[18] enabled approach to constructing requirements ontology

Problems in the context of requirements discussed in the literature review section lead to issues in communication and understanding. Ontologies are a means to solve these problems. The problems are solved by providing a formal, shared conceptualization of concepts and relationships in the context of interest using ontologies. As a result, this thesis investigates the research question *"what is a requirements ontology to guide the analysis of systems life cycle processes?"* To answer the question, the objective of the thesis is *"to propose a requirements ontology to guide the analysis of systems life cycle processes"*.

To meet the defined objective, the generic engineering research process by Breach (2009, p. 6) was tailored for this thesis. More specifically, this thesis addresses 3 major activities in the engineering research process: 1) choosing the methodology for data collection and analysis, 2) data collection, and 3) data analysis. Each of these activities is discussed in the remaining of this section.

3.1 Choosing a methodology for data collection and analysis

A methodology shall guide the selection and application of suitable approach and appropriate methods, and encourage reflection on the approach and methods to be used (Blessing & Chakrabarti, 2009, p. 9).

In general, the scope of a research methodology is defined in Fig. 13. T. A. Nguyen and Zeng (2012), authors of the figure, state that there are usually two approaches to validate a study in research: inductive and deductive. Considering the figure, the inductive approach deals with drawing conclusions as validation mechanism from experiments, case studies, and retrospection (Pruzan, 2016, p. 102). On the other hand, the deductive approach aims to reason about a theory/hypothesis[19] following first principles and logical inference (Pruzan, 2016, pp. 98-105).

[18] EBD stands for Environment-Based Design (Zeng, 2015).

[19] There are three related concepts in science: laws, theories, and hypotheses (Law, 2017). A law is a descriptive principle of nature that holds in all circumstances covered by the wording of the law (e.g., Boyle's law or law of conservation). A theory is a description of nature that encompasses more than one law but has not achieved the

The underlying idea of deduction is: one deduces a statement from other given statement; thus, if the given statements (aka premises) are true and the reasoning is valid, the deduction is valid – but not necessarily true, since the truth depends on the premises (Pruzan, 2016, p. 99). In general, deduction reasons from the general to the specific (one deduces a statement from other given statements), whereas induction reasons from the specific to the general (from specific observations to general conclusions) (Pruzan, 2016, p. 104). Both deduction and induction approaches end with conclusions. A conclusion is the result of an argument. An argument is a sequence of logical propositions based on a set of premises and leading to a conclusion (Law, 2017).

Considering the top part of Fig. 13, a theory enables deduction. The concept of theory has been originated from science (i.e., chemistry, physics, and biology), where major tenets in the definition involve explanation, body of hypotheses/facts/laws/principles, experimental observation, and revision/modification/disproval (Chang, 2008, p. 3; Reece et al., 2011, pp. G-35; Young & Freedman, 2012, p. 2). In agreement with the definition of theory in science, Eder (2014), Whetten (1989), and Ullman (1991) from the design community suggest that a design theory should answer six questions as a criteria to be considered a theory: what, how, why, who, where, and when. In order to answer those questions, EBD theory is adopted. The relationships between EBD theory and the questions are discussed in Section 3.1.1.

Experiments, case studies, and retrospection are also important components of Fig. 13 that specially support the inductive approach. An experiment or controlled experiment is characterized by measuring the effects of manipulating one variable on another variable and that subjects are assigned to treatments randomly (Montgomery, 2013, pp. 1-8; Runeson, Höst, Rainer, & Regnell, 2012, p. 12). A case study is an empirical method aimed at investigating contemporary phenomena in their context (Runeson et al., 2012, p. 12). Retrospection (i.e., a retrospective study) is a research that uses information from the past to draw conclusions (Blessing & Chakrabarti, 2009, pp. 104-106; Montgomery & Runger, 2011, pp. 5-6; Upton & Cook, 2014).

uncontroversial status of a law. A hypothesis is a theory or law that retains the suggestion that it may not be universally true.

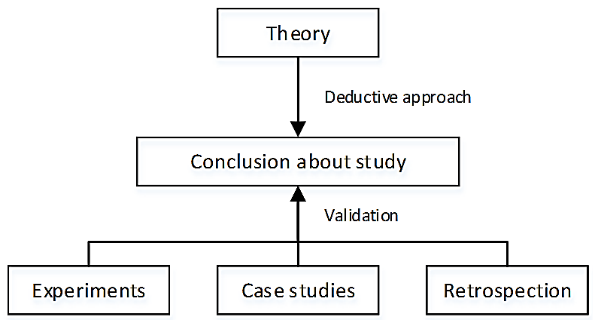


Fig. 13 Research methodology, adapted from T. A. Nguyen and Zeng (2012)

Although the directions towards conclusions in Fig. 13 look linear and rigid, they imply iterations, recursions, and feedbacks between the use of deduction and induction to draw conclusions in the research methodology. Iterations, recursions, and feedback happen by the fact that new knowledge is gained during the research process, which helps to clarify and reformulate the focus of the research study (Blessing & Chakrabarti, 2009, pp. 13-19). Iterations, recursions, and feedbacks can be noticed in the DRM framework in Fig. 14. Indeed, the objective of this research (i.e., *"to propose a requirements ontology to guide the analysis of systems life cycle processes"*) involves the mutual interaction and learning while using theory, experiments, case studies, retrospection and new knowledge (partial conclusions).

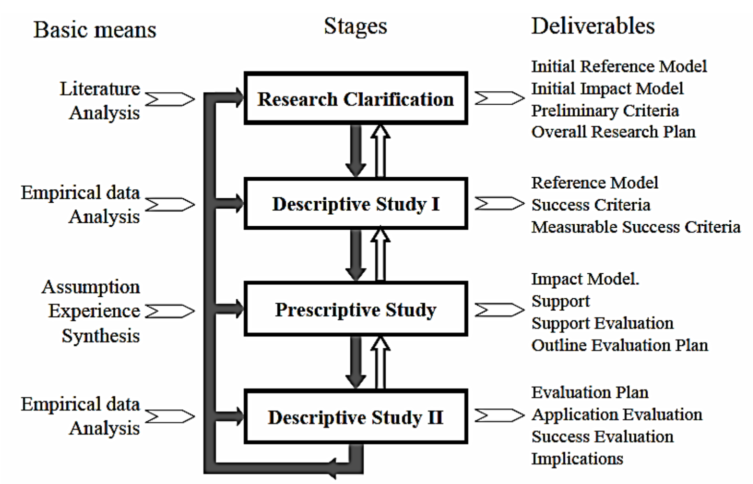


Fig. 14 DRM (Design Research Methodology) framework: stages, basic means and deliverables (Blessing & Chakrabarti, 2009, p. 39)

Ontologies are related to theories. The relation between theory and ontology is illustrated in Fig. 15, which updates Fig. 13. An ontology can serve as a specification of the assumptions, terms, or concepts underlying a particular field of knowledge (Law, 2017). For example, the Gene

Ontology (GO) project is an international collaboration between various databases in the field of genomics to standardize terminology used by researchers (Law, 2017). Such standardization is vital for efficient searching of databases, particularly for devising and using automated search programs. From this example, it can be inferred that unshared ontologies lead to different understanding of a domain of interest. Different understanding harms the creation of laws. For example, Boyle's law (a type of gas law[20]) states that the volume (V) of a given mass of gas at a constant temperature is inversely proportional to its pressure (p), i.e., pV = constant. If researchers cannot agree about what constitute a given mass, they cannot verify and validate the truth of the law. Laws evolve from theories. Theories are description of nature that encompasses more than one law but has not achieved the uncontroversial status of a law. If there are different unshared ontologies, so different understanding; then, there is also harm in the creation of theories and laws. Ontologies, laws, theories, and hypotheses progress together as new knowledge evolves.

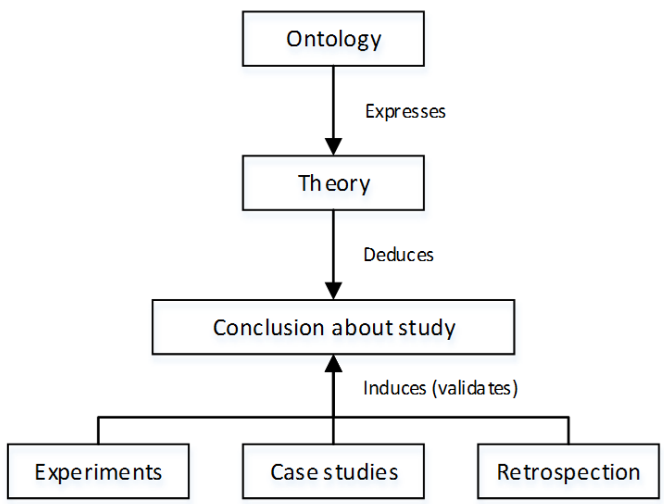


Fig. 15 Relationships between ontology, theory, conclusions, experiments, case studies, and retrospection

After defining several terms related to the research methodology in Fig. 15, the remaining of this section elaborates about the selected theory and conducted case studies (which also serve as a retrospection method). Each of these topics are further elaborated and discussed in Section 3.1.1 and Section 3.1.2.

[20] Gas laws relate to the temperature, pressure, and volume of an ideal gas (Law, 2017).

3.1.1 Theory: Environment-based design (EBD)

Based on Fig. 13, theory was the starting point of this research. More specifically, this research adopted Environment-Based Design (EBD) theory (Zeng, 2011, 2015). With respect to Fig. 14, EBD theory served as the initial reference model to achieve the research objective. A reference model represents the initial situation in the scope of research (Blessing & Chakrabarti, 2009, p. 20). However, as research has evolved, it has been found to reach agreement with the iterations, recursions, and feedbacks suggested by Blessing and Chakrabarti (2009, p. 17). This is what is also known as co-evolution of design (design problems, design solutions, and design knowledge) in EBD theory (Zeng & Cheng, 1991) (refer to Fig. 16).

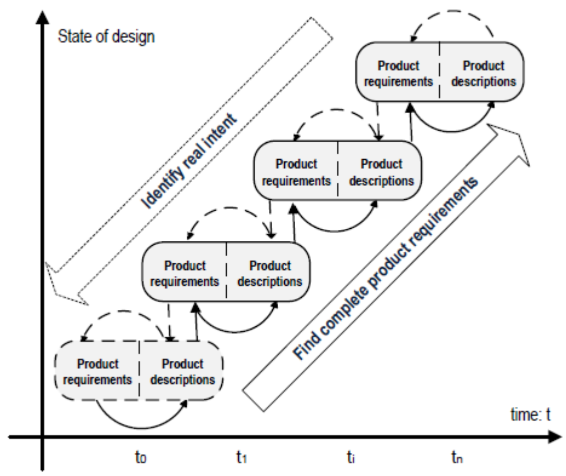
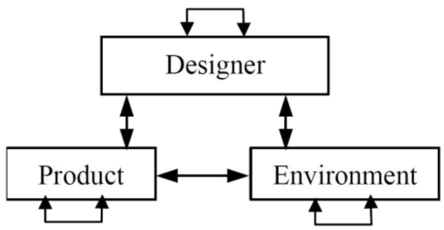


Fig. 16 Evolution of the design process (Zeng, 2015), originally from Wang and Zeng (2009)

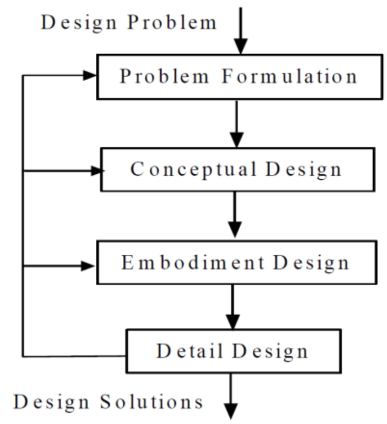
EBD theory meets the criteria to be considered a design theory. Zeng (2004a, 2004b, 2011, 2015) and Z. Chen and Zeng (2006) define the main concepts to explain and predict the behavior of a system (natural or artificial) in EBD theory. The root concepts are: *human environment, built environment, natural environment, life cycle, and design process*. These root concepts are defined in Table 5. In addition, the table associates the root concepts in EBD theory to the six questions to be considered a design theory. The root concepts in EBD theory has been defined and extracted from Fig. 17 and Fig. 18. Fig. 17 defines the scope of design science in terms of designer (human environment), product (system), environment (natural and built), and their relationships. The terms are defined in the left side of the figure. The right side of the figure suggests that design evolves iteratively and recursively through the design process. In addition to Fig. 17, Fig. 18 defines the role of the life cycle in design provided by interactions with the environment. The figure also illustrates instances of a generic life cycle model, and environment components.

Table 5 Root concepts in EBD theory

Concept	Definition	Question	Source
Environment	The environment is everything except the product (artifact) to be designed. The environment can be classified into natural, built, and human.	What, where, who, why, and how	(Zeng, 2015)
Natural environment	Natural environment refers to all the [natural] laws in the product's working environment.	What, where, why, and how	(Zeng, 2004a, 2015)
Built environment	Built environments are the artefacts designed and created by human beings (e.g., man-made devices).	What, where, who, why, and how	(Zeng, 2015)
Human environment	Human environments include all the human beings but particularly the human users of an artifact.	What, who, why, and how	(Zeng, 2015)
Life cycle	Phases (stages) occurring in the life of a product (e.g., design, manufacturing, sales, transportation, use, maintenance, and recycle).	When, where, how	(Z. Chen & Zeng, 2006)
Design process	The design process are the activities (i.e., environment analysis, conflict identification, and solution generation) executed to change an existing environment to a desired one by creating a new artifact into the existing one. Three important constituents in the design process are design solutions (concepts), design problems, and design knowledge.	When, where, how	(Zeng, 2015)



Object study of formal design science: arrows represent relationships



Basic design process

Fig. 17 Scope of design science (Zeng, 2004b)

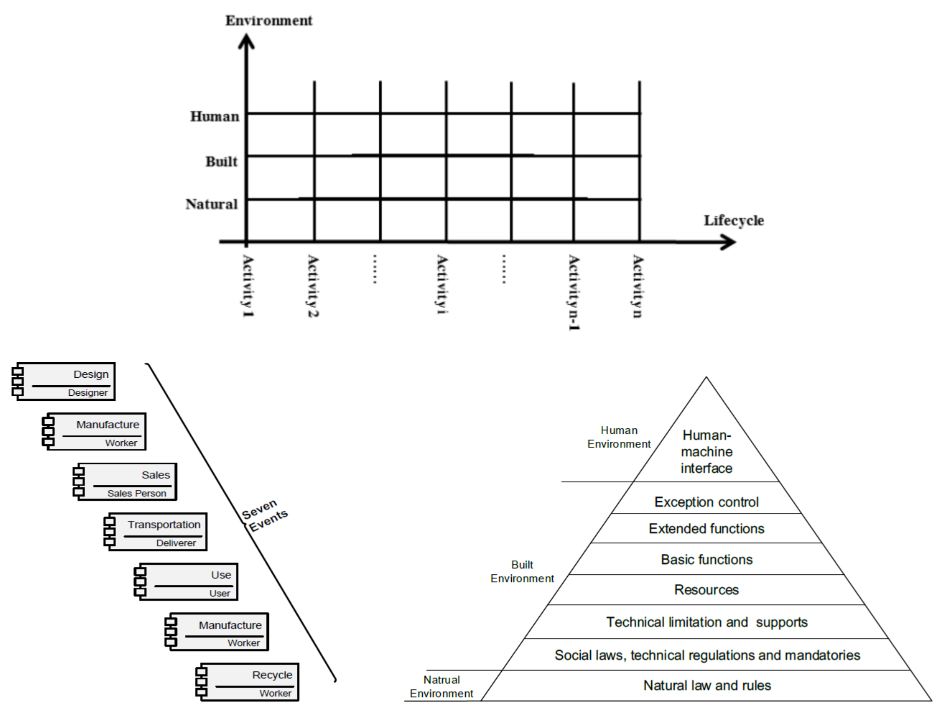


Fig. 18 Generic roadmap for domain related environments (Zeng, 2015)

The root concepts in EBD theory are the right semantic root concepts for an ontology. To justify this argument, two ontologies are used as benchmarks: Ahmed, Kim, and Wallace (2007), and ISO (2015a). The ontology proposed by Ahmed et al. (2007) for engineering design has four root concepts: design process, function, issue, and product. Based on the proposed root concepts in Table 6, the root concepts by Ahmed et al. (2007) can be categorized as follows - Ahmed's concept [EBD theory root concept, criteria of design theory]: design process [design process, how], function [environment, what], issue [design process, why/how], and product [built environment, what]. An alternative view of root concepts can be found in the international standard for quality management systems – fundamentals and vocabulary (ISO, 2015a). Based on the proposed root concepts in Table 6, the root concepts by ISO (2015a) can also be categorized as follows [EBD theory, criteria of design theory]: person or people [human environment, who], organization [human environment, who], activity [life cycle, when], process [design process/life cycle, when/how], system [environment, what], requirement [built environment, what], result [built environment, what], data, information and document [built environment, what], customer [human environment, who], characteristic [natural/built environment, what], determination [design process/life cycle/built environment, how], action [design process/life cycle/built environment, how], and audit [design process/life cycle/environment, how]. According to this brief evaluation, as a basis for validation, the root concepts in EBD theory are the right root concepts for an ontology.

EBD theory has been developed since the 1990s (Zeng & Cheng, 1991). Since then, EBD theory has progressed from being descriptive into being both descriptive and prescriptive (Zeng, 2015). Fig. 17 and Fig. 18 evidence the descriptive capability of EBD theory. An additional descriptive capability was added with the development of ATDM (Axiomatic Theory of Design Modeling) (Zeng, 2002) and ROM (Recursive Object Model) (Zeng, 2008). In the latest stage of development, EBD theory continues descriptive but also prescriptive. Prescriptive EBD stems from descriptive EBD theory. Prescriptive EBD can also be considered as a design methodology. Prescriptive EBD uses ROM and a systematic question asking approach to elicit product requirements (Wang & Zeng, 2009). The systematic question asking approach builds on ROM which is based on ATDM. ROM and the systematic question asking approach have been applied to develop case studies and to create the ontology in this research. Case studies are further discussed in Section 3.2, but the general EBD enabled approach to construct requirements ontology is defined in Fig. 19.

Table 6 Root components in the particular application of the ontology

		EBD theory				
		Natural environment	Built environment	Human environment	Life cycle	Design process
Criteria	What	Enabling natural resources and characteristics (e.g., physical, sensorial, behavioral, temporal, ergonomic, and functional), and natural laws	System of interest, system elements, enabling systems, and requirements	Stakeholders (internal and external) (e.g., supplier, acquirer, user, operator, etc.)		
	Where	Geographical locations (e.g., airports in Montreal and Toronto, Canada) with corresponding natural laws	Physical locations (e.g., infrastructure, facility)			
	When				Systems life cycle processes	Environment analysis, conflict identification, solution generation
	Who			Stakeholders		
	Why[21]	Ecological/environmental factors	Political, economic, technology, and legal	Social		Conflicts between / within environment components
	How	All potential combinations of what, where, when, who, and why. In other words, all potential combinations of environments (natural, built, and human), life cycle, and design process.				

[21] Natural, built, and human environments in the why dimension corresponds to PESTEL (Abuhav, 2017, pp. 9-12; Gimbert, 2011; ISO/IEC/IEEE, 2017).

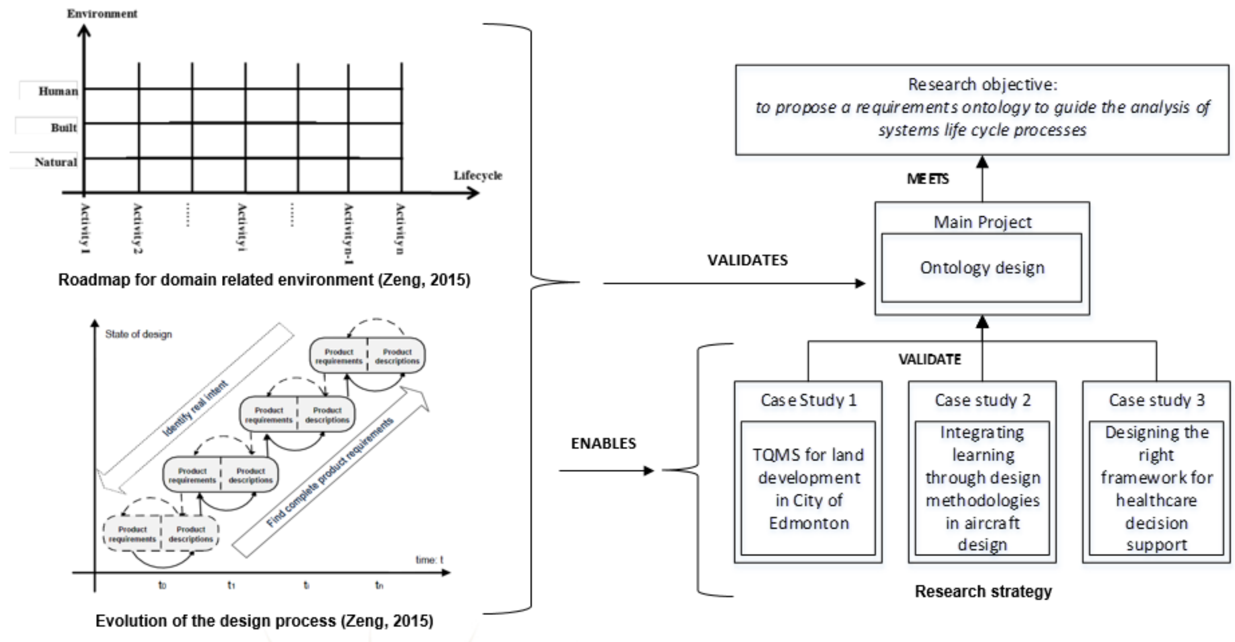


Fig. 19 Research strategy in this thesis: an EBD enabled approach to constructing requirements ontology

3.1.2 Data collection and data analysis

EBD theory serves as a research methodology for data collection and data analysis. EBD theory guides data collection based on its root concepts, ROM, and the systematic questions asking approach employed in case studies. The root concepts in EBD theory lead to identify relevant ontologies in the literature. ROM and the systematic questions asking approach in EBD theory are used to decompose semantically the research objective of this thesis. Implicitly, both ROM and the systematic questions asking approach have been employed in the literature review section. Case studies as data sources constructed based on EBD theory have also served to guide and partially validate the proposed ontology. In contrast to data collection, EBD theory does not guide directly data analysis. However, the root concepts in EBD theory (i.e., Table 5 and Table 6) can be verified and discussed qualitatively in the case studies as a form of retrospection as a basis to validate the proposed ontology. Data collection and data analysis are further discussed in Section 3.2 and Section 3.3 respectively.

3.2 Data collection

In general, there are several data collection methods in design research. Data collection methods in design research are: 1) observation, 2) simultaneous verbalism, 3) experiments, quasiexperiments, and non-experiments, 4) case studies, 5) collecting documents, 6) collecting products, 7) questionnaires, 8) interviews, and 9) action research) (Blessing & Chakrabarti, 2009, pp. 257-273).

This thesis adopted four of the suggested data collection methods. These methods are case studies, questionnaires, interviews, and collecting documents. The data collection methods have been applied in four kinds of projects. The projects are defined and related in the right side of Fig. 19. The projects were selected and performed based on available opportunities during the time of this research. This type of selection may hinder access[22] and control of data during a project. The projects are described in the subsequent paragraphs.

This thesis started data collection with a collaborative research project with the section of Area Development Planning at City of Edmonton, Alberta, Canada. This project is represented in the right side of Fig. 19 as case study 1. The project lasted 6 months from June to December in 2013. The main objective of the project was to create a guideline to develop a total quality management system for Area Development Planning. During the project, informal interviews help to clarify/understand the scope and objective of the project. After the interviews, questionnaires were created and used as data collection methods to understand workflows in the section of Area Development Planning. This collaborative research project resulted in case studies which facilitated to understand and apply EBD theory. Thus, this research project helped also to validate in general and to justify the adoption of EBD theory in this thesis research project.

A second project category of data collection is related to product design and development in the aerospace sector. These projects are represented in the right side of Fig. 19 as case study 2. Participation in this category of projects initiated in July 2014. Until the present, I have been participated formally and informally in this category of projects. During this time, there have been several meetings and two kinds of projects. Meetings have included presence of several stakeholders such as students, academics and industrial collaborators from institution operating in Montreal, Canada. Meetings help to clarify and understand the objective and scope of the projects.

[22] For instance, the literature review discusses two important aspects of ontologies: minimum information model and common information model. Researchers have tried to identify these models through survey or interviews (Miller et al., 2017; Quintana et al., 2010). Ideally, researchers can investigate these models through document analysis if they have access to such resources in relevant engineering projects (e.g., aerospace, automotive, infrastructure, healthcare, etc.). Considering that the latter is not the case in this research, case studies try to simulate real design process in order to identify these models. These cases are intended to validate the proposed ontology that comes from deduction and investigation of international research in the scope of the ontology.

It is important to point out that this category of projects have limited access to information and progression affected by organization restructuring, and the nature of the industry. In general, the scope of the first project was to understand customer requirements and to link them to product characteristics during conceptual aircraft design. The second project under the scope of NCADE (NSERC Chair in Aerospace Design Engineering) project involves collaboration to understand learning in the context of aerospace design. The two projects have helped also to understand and apply EBD theory in the context of aircraft conceptual design. Therefore, the projects have also served as evidence of the effectiveness of EBD theory for this research. In addition, the projects have facilitated to grasp the challenges associated to learning and communicating during the design process of interdisciplinary complex products such as aircrafts. From these projects, the need of ontologies to communicate design activities have been better clarified and understood. Such situation can be evidenced in the cartoon in Fig. 20.

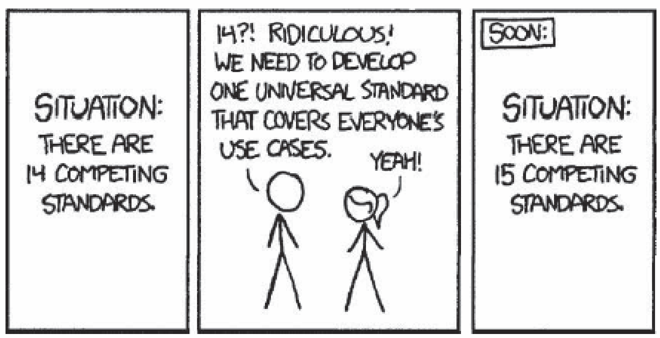


Fig. 20 Common situation in standard development (Greulich & Jawad, 2018, p. 1)

A third stream of project during this research is related to healthcare. This project is represented in the right side of Fig. 19 as case study 3. This project was in collaboration with a professor from the Health Management and Informatics, University of Central Florida, Orlando, USA. The project lasted about 2 months: started in January 2016 and ended in March 2016. During the project, emails and word documents were used to facilitate communication. The objective of this project was to write a research article. More specifically, the project created the article *"Designing the right framework for healthcare decision support"*. EBD theory and methodology were used to execute successfully the project. Success of EBD theory and methodology in the project is measured considering the resulting published research article, acknowledged communication effectiveness, and positive feedback from the collaborator. This project also helps to understand and apply EBD theory. Thus, the project helps to gain confidence to use EBD theory as the foundation to work on the research objective of this thesis.

Considering the experience and new knowledge gained during the previous three streams of collaborative projects, an independent endeavor started to achieve the objective of this thesis (i.e., *"to propose a requirements ontology to guide the analysis of systems life cycle processes")*. This project is represented in the right side of Fig. 19 as the master project. Unofficially, this project started since 2012. It is called unofficially because the previous projects and master research have helped to clarify, understand, and gain knowledge in the domain of the ontology. Officially, collecting documents for the project started with the preparation of the doctoral research proposal starting in 2017. Collecting documents available as research articles, publicly accessible research deliverables, or textbooks help to understand ongoing research efforts, results, and to work constructively towards achieving the research objective. These documents were mainly collected from three European research efforts from Germany, Netherlands, and the UK. The collected documents will be specified in the following sections of this thesis.

Data collection presented in this section covers at least two stages of the DRM framework in Fig. 14. The stages are: research clarification and descriptive study I (Blessing & Chakrabarti, 2009, pp. 15-16). The iterative nature of the activities has been discussed previously, but the two stages and suggested research projects are defined in Fig. 21. Fig. 21 lists 7 possible types of design research projects. Based on the figure, a review-based project should starts with a clarification of the research (RC stage) by reviewing the literature, to determine the aim, focus and scope of the research project (Blessing & Chakrabarti, 2009, p. 18). On the other hand, any comprehensive descriptive study (DS)-I should be followed by an initial prescriptive study to at least suggest how the findings could be used to improve design (Blessing & Chakrabarti, 2009, p. 19). This type of research is followed by any of the types of research, which are defined by Blessing and Chakrabarti (2009, p. 19). Thus, this research fits the type 1 design research project in Fig. 21: review-based project and comprehensive DS-I project. The first 4 types of design research projects in Fig. 21 are suitable for PhD projects (Blessing & Chakrabarti, 2009, p. 19).

Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1. Review-based →	Comprehensive		
2. Review-based →	Comprehensive →	Initial	
3. Review-based →	Review-based →	Comprehensive →	Initial
4. Review-based →	Review-based →	Review-based → Initial/ Comprehensive ←	Comprehensive
5. Review-based →	Comprehensive →	Comprehensive →	Initial
6. Review-based →	Review-based →	Comprehensive →	Comprehensive
7. Review-based →	Comprehensive →	Comprehensive →	Comprehensive

Fig. 21 Types of design research projects and their main focus (iterations omitted) (Blessing & Chakrabarti, 2009, pp. 18-19)

The rest of this thesis follows the projects discussed in data collection. From Fig. 19, the rest of this thesis is organized as illustrated in Fig. 22. In fact, as the projects discussed in the case studies were conducted before and unrelated to the creation of the proposed ontology, they serve as a form of retrospection to validate the ontology.

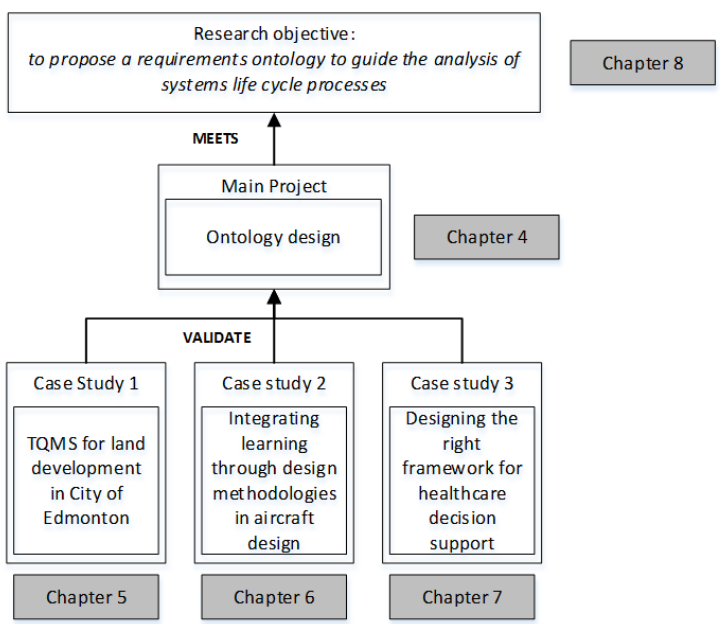


Fig. 22 Thesis organization to meet research objective

3.3 Data analysis

Data analysis evolves with data collection (Runeson et al., 2012, p. 62). There are 3 kinds of data analysis techniques used in design science research. These techniques are: content analysis, discourse analysis, and statistical analysis (Blessing & Chakrabarti, 2009, pp. 273-276; Dresch, Pacheco, & Valle, 2015, pp. 29-35; Runeson et al., 2012, pp. 61-76). Statistical analysis is used in conjunction with either content analysis or discourse analysis. In general, this research adopts content analysis in conjunction with statistical analysis (i.e., descriptive statistics).

Content analysis follows the EBD enabled approach to constructing requirements ontology. An EBD enabled approach to constructing requirements ontology can happen in several paths. Different paths can come from the root concepts in EBD defined in Table 6. For example, a first path of content analysis can happen from a life cycle perspective (M. Chen, 2006; Z. Chen, 2006; Z. Chen & Zeng, 2006). This path enables to encode data using a life cycle roadmap and corresponding environment components (see Fig. 18) as common frame of reference. A second path of content analysis can follows the design process (P. Nguyen, Nguyen, & Zeng, 2018a, 2018b; T. A. Nguyen, Xu, & Zeng, 2013; Petkar, Dande, Yadav, Zeng, & Nguyen, 2009; Tang & Zeng, 2009; Zhu, Yao, & Zeng, 2007). This path enables to encode data at a micro-level using the design process from a designer or team of designers' point of view. Alternatively, a third path can use the environments to encode data related to each of the environments (Zeng, 2004a). Each of these paths need to have data at different level of details. Considering that this thesis intends to describe a greater context in the subject of ontologies, data analysis follows an alternative path. Data analysis uses the whole context defined in Table 6. This analysis may be hindered by low level of details of content analysis, but it benefits a greater overview in the context of the ontology. So, content analysis is intended to validate the proposed ontology in the general context of the root concepts of EBD and the associated competency (i.e., criteria) questions in Table 6.

Chapter 4: Ontology design – an EBD enabled approach to constructing requirements ontology

4.1 Introduction

The objective of this chapter is to *"propose a requirements ontology to guide the analysis of system life cycle processes"*. The motivation of working towards this objective was discussed in the introduction and literature review chapters. Considering such motivation, this chapter presents the design of an ontology to overcome challenges in communicating and understanding requirements during design activities. Requirements and design activities progress following system life cycle processes during a project. This chapter corresponds to ontology design highlighted in Fig. 22.

To synthesize the motivation of improving communication and understanding challenges associated to requirements through ontologies, the communication model of a shared ontology to enable communication in heterogeneous environments from the literature review chapter is revisited. The model is presented in Fig. 11. In particular, the needed ontology addresses the center of the model: content, domain of discourse, and specific content (Rachuri et al., 2008). These three components are represented by considering domain knowledge such as systems, systems life cycle processes, and requirements. Indeed, the resulting ontology seeks to define a minimum information model (MIM) in this domain knowledge, as defined in Fig. 7. The minimum information model defines the right semantics (i.e., common vocabulary) to improve communication and understanding of requirements in the domain knowledge. This semantics is formalized and explicitly specified through ROM representations (Zeng, 2008). Both semantics from the domain knowledge and formalizing an explicit specification through ROM conform the characteristics of a good ontology. Considering that the characteristics associated to syntax and formality of a good ontology in the context of this thesis have been investigated in previous research efforts at the Concordia University design lab (Z. Chen et al., 2007; Gonzalez, 2008; Rodica, 2011; Wan et al., 2016; Wang et al., 2013; Zeng, 2002, 2008), this chapter seeks to find the minimum information model in the domain knowledge considered as semantics. The right semantics are needed to improve communication and understanding of requirements. Therefore, integrating the domain knowledge into an ontology is one of the greatest contributions in this chapter and thesis. Such integration into an ontology is validated and enabled through EBD methodology (i.e., environment analysis, conflict identification, and solution generation) and EBD theory root concepts (i.e., natural environment, built environment, human environment, life cycle, and design process) (Zeng, 2015). The resulting ontology can be used as a coordination mechanism also depicted in the communication model in Fig. 11. The communication mechanism is not investigated at the current stage of the ontology design in this thesis. But, the communication mechanism is needed to guide effectively and efficiently the analysis of system life cycle processes (Suss & Thomson, 2009).

Based on the found challenges, and ontologies as a means of solution in thesis; this chapter has 5 contributions. The contribution are: 1) applying a step by step ontology design process that can be reused for learning purposes, 2) defining concepts and relationships in the domain of the ontology collected from different research groups, 3) reducing the number of concepts into minimum information models (i.e., lightest ontologies) through concept frequency analysis enabled by two international standards[23], 4) integrating the reduced number of concepts and relationships into one proposed core ontology, and 5) proving that the proposed core ontology is valid. The rest of this chapter is organized as summarized in Table 7; which also defines where to locate the contributions.

4.2 Requirements for the ontology

On key process in design is to write requirements into specifications. In order to write requirements into a specification, the prescriptive and detailed methodological guidelines for specifying ontologies by Suárez-Figueroa, Gómez-Pérez, and Villazón-Terrazas (2009) is adopted. The guidelines prescribe 8 tasks: 1) identify purpose, scope and implementation language, 2) identify intended end-users, 3) identify intended uses, 4) identify requirements, 5) group requirements, 6) validate the set of requirements, 7) prioritize requirements, and 8) extract terminology and its frequency. Each of this step is developed in the remaining of this section.

[23] The minimum information model is inferred from frequency analysis relative to the investigated concepts. This approach of inference may have some limitations. Requirement’s documents from successful and complete projects may enable to challenge the current limitation, and indeed, to provide the right minimum information models.

Table 7 Summary, table of content, and contributions for the rest of the chapter

Section #	Section name	Purpose	Contribution
4.2	Requirements for the ontology	Present 8 steps in the ontology design process. Steps include: 1) identify purpose, scope, and implementation language, 2) identify intended end-users, 3) identify intended uses, 4) identify requirements, 5) group requirements, 6) validate set of requirements, 7) prioritize requirements, and 8) extract terminology and its frequency.	1
4.3	Environment analysis	Propose a requirements ontology to guide the analysis of system life cycle processes by extending step 8 in previous section and applying the general idea of environment analysis in EBD methodology. Extensions include 5 sub-steps: 1) identify root concepts of taxonomies, 2) identify existing taxonomies, 3) create taxonomies, 4) test for applications, 5) and build thesaurus of terms.	2, 3, 4, 5
4.4	Conflict identification	Identify existing gaps (limitations) in the proposed ontology and the ontology design process during environment analysis.	5
4.5	Solution generation	Suggest guidance to address the identify gaps during conflict identification.	5
4.6	Conclusions	Recap achievement during all the previous sections. Present high-level idea of ontology enabled guidance for analysis of system life cycle process to be investigated as future work.	N/A

4.2.1 Step 1: Identify purpose, scope, and implementation language

4.2.1.1 Purpose

The purpose of the ontology is to overcome current communication challenges in designing multidisciplinary complex products. Thus, this ontology is for people's communication purposes.

4.2.1.2 Scope

Considering the purpose of the ontology, the scope shall represent the domain of requirements (ISO/IEC/IEEE, 2011) in the context of system life cycle processes (ISO/IEC/IEEE, 2015). Level of details for the defined scope of the ontology will be investigated and evaluated in subsequent developments in this chapter.

4.2.1.3 Implementation language

Among the existing languages to represent ontologies presented in the literature review, the ontology is implemented using ROM (Zeng, 2008). The selection of ROM is based on three reasons: 1) ROM is easier to learn (i.e., time and effort) than other languages (Wen et al., 2012) for new and existing users, 2) ROM may support automation, 3) ROM supports EBD theory and methodology (which is under development at the Concordia University Design lab, where the author of this thesis has been serving as research assistant since 2012). In addition, previous research (Wan et al., 2016; Wang et al., 2013) evidences that it is possible to translate ontologies from ROM to other languages (e.g., SysML).

The elements in ROM representations are: objects and relations (Zeng, 2008). Objects can be single objects and compound objects. Objects are used to represent words in the part of speech (Zeng, 2008). Different parts of speech are: nouns (e.g., paper), verbs (e.g., write), adjectives (e.g., good), determinatives (e.g., some), adverbs (e.g., well), prepositions (e.g., in), coordinators (e.g., and), and subordinators (e.g., that) (Huddleston & Pullum, 2005, pp. 16-22). Relations can be constraints, connection, and predicate used to words in parts of the speech (Zeng, 2008). Relations are used to represent the syntax governing how words can be assembled together into phrases, sentences or a cohesive whole (e.g., paragraphs or entire document), as interpreted from Zeng (2008). Relations are also used to represent the syntax governing how phrases, sentences, and paragraphs can be assembled together (e.g., comma, colon, semi-colon, period, question-mark, etc.) (Zeng, 2008); but this kind of relations is not applicable for expressing ontology in ROM in this thesis. The elements with their respective graphical representations are summarized in Fig. 23. Fig. 24 illustrates a ROM representation using the graphical representations corresponding to the title of this thesis.

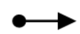
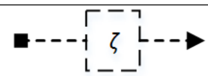
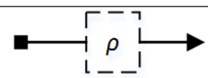
Type	Subtype	Graphic representation	Definition
Object	Single object (SO)	SO	Everything in the universe is an object.
	Compound object (CO)	CO	It is an object that includes at least two other objects in it.
Relations	Constraint		It is a descriptive, limiting, or particularizing relation of one object to another.
	Connection		It is to connect two objects that do not constrain each other.
	Predicate		It describes an act of an object on another or that describes the states of an object.

Fig. 23 Elements of ROM (Zeng, 2008, 2015)

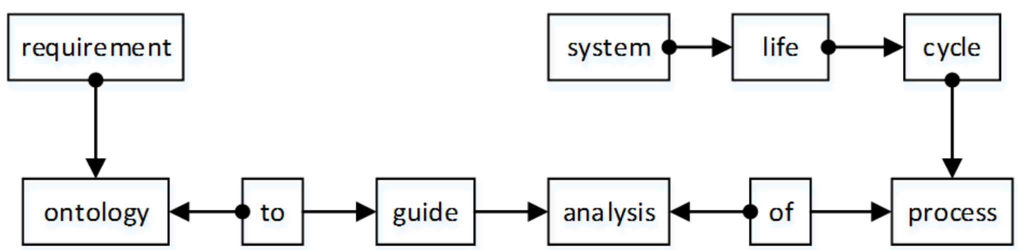


Fig. 24 ROM representation of the thesis title

4.2.2 Step 2: Identify intended end-users

End-users of the ontology are diverse. At this point, the intended end-users are researchers at the design lab, current and new students learning EBD theory and methodology, the international design science research community, the international systems engineering research community, and industry collaborators. In fact, the final goal is to support end-users in a variety of innovative system design projects.

4.2.3 Step 3: Identify intended uses

The intended use of the ontology is to support activities in EBD theory and methodology. Therefore, the scenarios of usage are: environment analysis, conflict identification, and solution generation. These activities can be better understood from the developed case studies in the next chapters. Future uses involve to support specific guidance to analyze system life cycle processes (INCOSE, 2004, pp. 154-178). These analyses are sometimes known as ilities or specialty engineering (INCOSE, 2015, pp. 211-241).

4.2.4 Step 4: Identify requirements

Requirements are classified into non-functional and functional requirements. Non-functional requirements includes: 1) the ontology shall be based on peer-reviewed publications with relevant ontologies, 2) the ontology shall be based on standards with relevant terminology, 3) the ontology shall be based on external work (i.e., design theory and case studies), 4) the ontology shall be written in ROM using English, and 5) the ontology shall have the characteristics of a good ontology as concluded in the literature review section.

Functional requirements for the ontology come from the root concepts in EBD theory: environments (natural, human, and built), process, and life cycle. Root concepts in EBD theory are related to key terms in the objective of this thesis. The objective of the thesis suggests investigating three areas: system, system life cycle processes, and requirements. These areas of requirements are detailed in the ROM representation for the title of this thesis in Fig. 24. The figure also suggests investigating analysis / guide analysis[24]; however, considering the current complexity of the ontology, this topic is not addressed at this time. Thus, as part of functional requirements, the ontology shall include the following concepts: environment (natural, human, and built), process, life cycle, system, and requirements. These concepts are associated to competency questions (i.e., criteria) as previously defined in Table 6.

Finally, the ontology excludes ontology life cycle requirements at this point (Neuhaus, Ray, & Sriram, 2014, p. 57). The exclusion is applicable at this initial stage of ontology design, but

[24] This topic implies to create/investigate methods to use the proposed ontology with new or existing requirements engineering methods (e.g., Quality Function Deployment, Design Structure Matrix or N^2, Analytical Hierarchical/Network Process, Kano model, and project management) to execute requirements engineering (Bahill & Dean, 2009; Grady, 2006; ISO/IEC/IEEE, 2011).

these requirements shall be considered in future developments of the ontology. The exclusion suggests that there are not requirements from the built environment different from the one defined previously as non-functional requirements. In addition, the exclusion suggests that there are not requirements from the natural and human environment different from ease of use for people communication. Nonetheless, ease of use for people communication is addressed by employing ROM to represent the ontology.

4.2.5 Step 5: Group requirements

Non-functional requirements were listed in Section 4.2.4. Functional requirements are grouped in Fig. 25. The table groups functional requirements into competency questions and root concepts in EBD theory. The requirements are synthesized in Fig. 25.

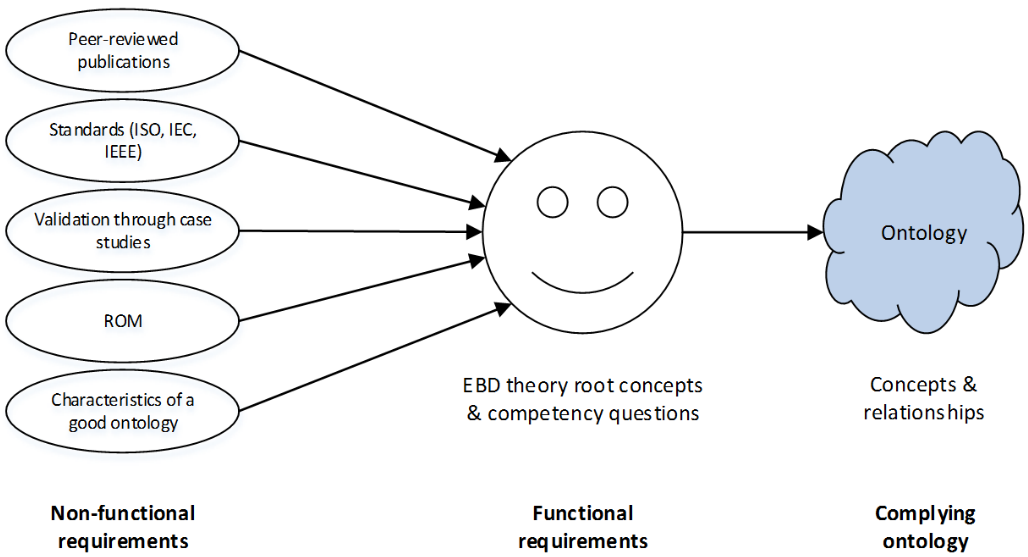


Fig. 25 Group of ontology requirements: towards a complying ontology

4.2.6 Step 6: Validate the set of requirements

In order to validate the proposed set of requirements, certain criteria shall be met. Suárez-Figueroa et al. (2009) suggest the following criteria: correct, complete, internally consistent, verifiable, understandable, unambiguous, concise, realist, and modifiable. To prove that the criteria are met, evidence comes from the presented case studies and the literature review. Root concepts in EBD theory have been proved to be effective describing and conducting the presented case studies. Thus, Table 8 presents specific proof of validation for the set of requirements in the ontology.

Table 8 Validating set of requirements for the ontology

Criteria	Proof of validation	
	Non-functional requirements (NFR)	Functional requirements (FR)
Correct	NFR limits the source of content, representation, characteristics of a good ontology, and how to validate it.	Competency questions and EBD theory root concepts describe initial context of use of the ontology.
Complete	Selected NFRs enable to obtain the characteristics of a good ontology in terms of syntax and semantics.	EBD theory root concepts enable to obtain the characteristics of a good ontology in terms of semantics.
Internally consistent	ROM enables to eliminate potential syntactical conflicts coming from the sources to be investigated.	ROM enables to solve semantically potential conflicting concepts in the domain of the ontology.
Verifiable	NFR and FR can be verified based on the design process and references employed in this and coming chapters.	
Understandable	Requirements were written in natural language using syntax patterns in natural language defined by Z. Chen et al. (2007). Supporting references and previous chapters also help to understand the requirements.	
Unambiguous	Requirements were written in natural language, but formalized/disambiguated using syntax patterns defined by Z. Chen et al. (2007).	
Concise	Each requirement is independent from each other; thus, there is no duplication. Each requirement is relevant to obtain the characteristics of a good ontology.	Competency questions are answered through EBD theory root concepts, so both are relevant and enable conciseness in order to obtain the characteristics of a good ontology.
Realist	NFR and FR are needed to create a good ontology.	
Modifiable	Requirements can be modified depending on the purpose, scope, users, and intended-uses of the ontology; but the characteristics of a good ontology shall always be met.	

4.2.7 Step 7: Prioritize requirements

Considering that the ontology is generic, and it is at the initial stages of development; all the requirements have the same degree of importance. The same degree of importance enables to understand the initial scope and work content needed to satisfy each requirement. Based on this understanding, future development and refinement of the ontology can have a baseline to prioritize requirements.

4.2.8 Step 8: Extract terminology and its frequency

This step is generally developed employing EBD methodology (Zeng, 2015). EBD methodology suggests activities such as environment analysis, conflict identification, and solution generation. Indeed, these activities implicitly lead to conduct data collection and data analysis. More specifically, extraction of terminology (i.e., data collection) and its frequency (i.e., data analysis) is done in the environment analysis activity. Hence, the rest of step 8 is presented in Section in Section 4.3. Conflict identification and solution generation activities (i.e., Section 4.4 and Section 4.5) also deal with data analysis, but in the context of limitations and future work in particular.

4.3 Environment analysis

The traditional environment analysis activity in EBD methodology was tailored for the purpose of designing the ontology. All the concepts in Fig. 24 were already introduced in the literature review section. Therefore, we omit to repeat the question-asking strategy in environment analysis to define them (Zeng, 2015).

The purpose of environment analysis is to define an environment system (Zeng, 2015). An environment system can be interpreted as objects and relationships (i.e., system and its environment) expressing a context (i.e., universe of discourse). A general definition of a product environment system is represented in Fig. 26, where $\oplus$ represents structure operation[25], and $\otimes$ represents the general idea of interactions/relations between objects (Wang et al., 2013; Zeng, 2002). Therefore, the purpose of environment analysis can be deduced to be the creation of an ontology (i.e., system) expressing requirements for system life cycle processes (i.e.,

[25] Structure operation ($\oplus$) is defined as the union ($\cup$) of an object (O) and the interaction/relation ($\otimes$) with of the object with itself (Wang et al., 2013).

environment). Any means to achieve this purpose is an alternative or complementing method to traditional environment analysis in EBD methodology.

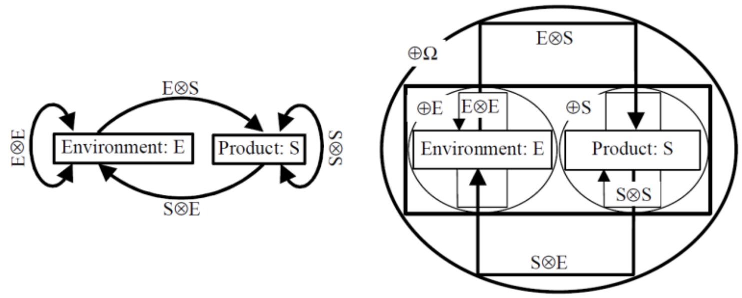


Fig. 26 Product environment system: engineering system (Ω) (Zeng, 2002)

Table 9 Methodology for creating ontologies for engineering design, constructed based on Ahmed et al. (2007)

Step	Research method	Evaluation method
Identify root concepts of taxonomies	EBD theory	Based on EBD theory
Identify existing taxonomies	Literature review	Relative comparison of identified ontologies based on syntax & formality, and semantics (number of concepts and types and number of relationships).
Create taxonomies	Statistical analysis & set operations	Based on inclusion of overlapping concepts from ISO/IEC/IEEE (2015), ISO/IEC/IEEE (2011) with identified ontologies
Test for application	Retrospective methods[26]	EBD theory enables to test the ontology deductively. The design process enables to find errors during this initial development. Finally, case studies (following chapters) enable to test the ontology in an external context.
Build thesaurus of terms	Literature review	Based on standards and reviewed references

[26] Retrospective data collection methods in design research can be documents (case history compilation, archival analysis), product data, questionnaires (e.g.., open ended), and interviewing (Blessing & Chakrabarti, 2009, pp. 104-105).

In this case study, environment analysis was executed following the alternative steps by Ahmed et al. (2007). The steps are: 1) identify root concepts of taxonomies, 2) identify existing taxonomies, 3) create taxonomies, 4) test for application, and 5) build thesaurus of terms. Each of the steps is developed in the remaining of this section. The employed research and evaluation methods for each step are described in Table 9.

4.3.1 Step 8.1: Identify root concepts of taxonomies

A taxonomy is a scheme that partitions a body of knowledge and defines the relationships among the pieces (ISO/IEC/IEEE, 2017). Root concepts in the ontology are based on EBD theory and concepts from the objective of this thesis guides the scheme in the taxonomy. As a result, the root concepts are: 1) environment, 2) process, 3) life cycle, 4) requirements, and 5) systems. Table 6 expanded and related these concepts.

4.3.2 Step 8.2: Identify existing taxonomies

Existing taxonomies in this thesis were extracted from three different European research efforts. These efforts are called in this thesis: COMPASS research project, German research group, and Leo van Ruijven, Croon Elektrotechniek from the Netherlands. The three efforts investigate aspects associated to the root concepts in EBD theory. Raw data (i.e., concepts and relationships) extracted from these efforts is detailed in Appendix A. The same appendix compares the identified taxonomies in terms of 1) syntax & formality, 2) number of concepts, and 3) relationships. The appendix ends by consolidating and integrating into a list of 23 concepts: 1) activity, 2) interface, 3) requirement, 4) stakeholder, 5) need, 6) standard, 7) availability, 8) flexibility, 9) functional requirement, 10) interaction, 11) issue, 12) organization, 13) port, 14) process, 15) project, 16) quality, 17) reliability, 18) safety, 19) service, 20) stakeholder requirement, 21) system, 22) system element, and 23) system requirement. Although a taxonomy is a schema that shall relate these concepts, this step ends with the list of concepts. The reason of this decision is that Section 4.3.3 expands this number of concepts. However, these concepts will be related with the list of 194 relationships consolidated in Appendix A (Section A.4.2).

4.3.3 Step 8.3: Create taxonomies (ontologies)

Taxonomies represent the shared conceptualization in an ontology, interpreted as semantic meaning in this thesis (van Rees, 2003). As major concerns in this thesis deal with semantic meaning, a taxonomy is also considered as an ontology for simplification purposes in terminology usage. However, a major difference between taxonomies and ontologies is that the former only defines hierarchical composition of classes missing potential existing association in or between classes. The missing part is needed to have full semantics of a domain where ontologies extend the semantic richness (e.g., part-part and part-whole associative relationships) of taxonomies.

The rest of this section develops two subjects. Subject 1 discusses the creation of concepts and relationships for the proposed ontology (Section 4.3.3.1). Subject 2 develops the creation of the proposed ontologies in this thesis (Section 4.3.3.2).

4.3.3.1 Creation of concepts and relationships for the proposed ontology

This task evaluated and expanded the list of concepts and relationships defined in step 8.2. The evaluation and expansion happened by introducing concepts two international standards: ISO/IEC/IEEE (2015) and ISO/IEC/IEEE (2011). The evaluation and expansion employed union and intersection operations in set theory. The evaluation and expansion concluded by defining the 50 concepts in Table 10. Therefore, this table incorporated 27 more concepts to the list of 23 concepts defined in step 8.2. Further details about the evaluation and expansion of concepts is provided in Appendix B. These concepts will be related with the list of 194 relationships consolidated in Appendix A (Section A.4.2). Concepts and relationships conform the proposed ontologies in Section 4.3.3.2.

Table 10 Concepts for a requirement ontology to guide the analysis of system life cycle processes: sorted by Sum column

#	Concept	COMPASS research group	German research group	Leo van Ruijven	ISO 15288	ISO 29148	SUM
1	Requirement	1	1	1	1	1	5
2	Stakeholder	1	1	1	1	1	5
3	Activity	1	1	1	1	0	4

4	Customer	0	1	0	1	1	3
5	Interface	1	1	1	0	0	3
6	Organization	1	0	1	1	0	3
7	Process	1	0	1	1	0	3
8	Project	1	0	1	1	0	3
9	Service	1	0	1	1	0	3
10	System	1	0	1	1	0	3
11	System element	1	0	1	1	0	3
12	User	0	1	0	1	1	3
13	Acquirer	0	0	0	1	1	2
14	Architecture	1	0	0	1	0	2
15	Attribute	0	1	0	0	1	2
16	Availability	0	1	1	0	0	2
17	Baseline	0	0	0	1	1	2
18	Concept of operations	0	0	0	1	1	2
19	Concern	1	0	0	1	0	2
20	Document	0	0	1	0	1	2
21	Enabling system	1	0	0	1	0	2
22	Environment	0	0	1	1	0	2
23	Flexibility	0	1	1	0	0	2
24	Functional requirement	1	0	1	0	0	2
25	Interaction	0	1	1	0	0	2
26	Issue	0	1	1	0	0	2
27	Life cycle	1	0	0	1	0	2
28	Life cycle model	1	0	0	1	0	2
29	Need	1	1	0	0	0	2
30	Operational concept	0	0	0	1	1	2
31	Operator	0	0	0	1	1	2
32	Party	0	0	1	1	0	2
33	Port	1	0	1	0	0	2

34	Product	1	0	0	1	0	2
35	Quality	0	1	1	0	0	2
36	Quality management	0	1	0	1	0	2
37	Reliability	0	1	1	0	0	2
38	Resource	1	0	0	1	0	2
39	Risk	0	0	1	1	0	2
40	Safety	0	1	1	0	0	2
41	Stage	1	0	0	1	0	2
42	Stakeholder requirement	0	1	1	0	0	2
43	Standard	1	1	0	0	0	2
44	State	0	1	0	0	1	2
45	Supplier	0	0	0	1	1	2
46	System requirement	0	1	1	0	0	2
47	System-of-interest	0	0	0	1	1	2
48	Trade-off	0	0	0	1	1	2
49	Validation	0	0	0	1	1	2
50	Verification	0	0	0	1	1	2
---	TOTAL	22	20	25	33	17	117

4.3.3.2 Creation of ontologies

For learning purposes, lighter ontologies can be created until progressing to the one with the 50 core concepts in Table 10. Lighter ontologies can be identified from Table 10. Based on the frequency of concepts in the sum column in the table, lighter ontology can be created. In total, four types of ontologies can be created grouping the colors in the table moving from top to the bottom in the sum column. The lightest ontology only includes two concepts: requirement and stakeholders. The second lightest ontology includes three concepts: requirement, stakeholder, and activity. The third lightest ontology includes 12 concepts: requirement, stakeholder, activity, customer, interface, organization, process, project, service, system, system element, and user. The least light ontology (i.e., the core proposed ontology) includes all the concepts in Table 10. The concepts in the ontologies shall be integrated based on the verb phrases in the list of 194 relationships consolidated in Appendix A (Section A.4.2). Positive active voice statements (arguments) to integrate concepts and relationships are preferred instead of negative active voice or passive voice ones. Therefore, the verb phrases in in the list of 194 relationships can be transformed and interpreted from passive to active voice in the ontologies as needed. Each of the suggested ontologies is presented and discussed in the remaining of this section.

4.3.3.2.1 The lightest ontology

The lightest ontology only includes two concepts: requirement and stakeholders. A ROM representation integrating the concepts is defined in Fig. 27. The ROM representation is an expression of the lightest ontology. The ROM representation is created based on the interpretation and knowledge of the author of this thesis.

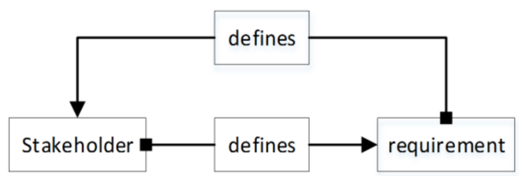


Fig. 27 The lightest ontology

The two concepts are integrated based on recursively dependent logic in Fig. 27. Recursively dependent logic comes from the interpretation of the author of this thesis from the logic of design discussed by Zeng and Cheng (1991). This logic means that each statement in the ontology, relating concepts through relationships, may have at least one corresponding recursively dependency. The corresponding recursively dependency can be composed of one or many statements. The corresponding recursively dependency can be interpreted as the biconditionals statement[27] (aka bi-implications, if and only if, iff, *statement x* ↔ *statement y*, or *statement x* is necessary and sufficient for *statement y*) to make the same truth value of converse (i.e., *statement y* → *statement x* is the converse of *statement x* → *statement y*), contrapositive (i.e., ¬ *statement y* → ¬ *statement x* is the contrapositive of *statement x* → *statement y*), and inverse (¬ *statement x* → ¬ *statement y* is the inverse of *statement y* → *statement x*) in propositional logic (Rosen, 2012, pp. 8-10). Biconditionals statement makes truth values when both conditional statements (*statement x* → *statement y* and *statement y* → *statement x*) are true and false otherwise. For example, Fig. 27 define the statement: *if stakeholder defines requirement, then requirement defines*

[27] Biconditionals are usually implicit in natural language (Rosen, 2012, p. 10).

stakeholder. The converse, contrapositive and inverse of the statement are defined in Table 11. All the statements in the table shall make the same truth value. Therefore, the statements are axiom in the ontology (Dou & McDermott, 2006). The logic in the statement is used to develop/interpret the ontology in Fig. 27.

Table 11 Cases and example: converse, contrapositive, and inverse

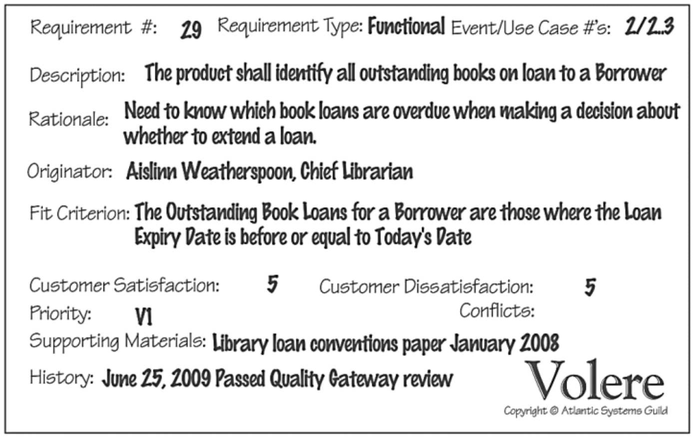
Case	Example
Converse	If requirement defines stakeholder, then stakeholder defines requirement.
Contrapositive	If requirement does not define stakeholder, then stakeholder does not define requirement.
Inverse	If stakeholder does not define requirement, then requirement does not define stakeholder.

Concepts and relationships in the ontology form statements. Patterns of statements in written technical English are discussed by Zeng (2008), Z. Chen et al. (2007), or Kolln and Funk (2012, p. 31). But, Zeng (2008)'s patterns are specifically adopted in representing the ontology. Based on those patterns, the statements in Table 12 can be extracted from the ontology in Fig. 27. The statements are grouped and listed as statement 1 because they together define the previously discussed biconditionals.

Table 12 List of statements in the lightest ontology

#	Statement and relationships (red) – Necessary (N) and sufficient (S) conditions	Source of relationship in list in Appendix A (Section A.4.2)
1	Stakeholder defines requirement (N). Requirement defines stakeholder (S).	5

From meaning point of view, the idea of the statements in the lightest ontology can be interpreted by using the attributes of an atomic requirement in Volere. Stakeholders define the requirements, in reponse the atomic requirement has an attribute called stakeholder. The atomic requirement in Fig. 28 names the stakeholder as the originator. The creation of the ontology at this stage of development only use the general idea of an atomic requirement in Volere. Therefore, future work needs to be done to identify what are the right attributes in an atomic requirement and how to interpret/extract them from the created ontology.


Requirement #: 29 Requirement Type: Functional Event/Use Case #'s: 2/2.3

Description: The product shall identify all outstanding books on loan to a Borrower

Rationale: Need to know which book loans are overdue when making a decision about whether to extend a loan.

Originator: Aislinn Weatherspoon, Chief Librarian

Fit Criterion: The Outstanding Book Loans for a Borrower are those where the Loan Expiry Date is before or equal to Today's Date

Customer Satisfaction: 5 Customer Dissatisfaction: 5

Priority: V1 Conflicts:

Supporting Materials: Library loan conventions paper January 2008

History: June 25, 2009 Passed Quality Gateway review

Volere

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Fig. 28 An example of the attributes of an atomic requirement (Robertson & Robertson, 2009)

The approach presented to create the lightest ontology is used to create the rest of ontologies. Evidently, all the ontologies are integrated. Integration means that the lightest ontology (LO) conforms the second lightest ontology (SLO), the third lightest ontology (TLO), and the core ontology (CO). From subsets point of view (Rosen, 2012, p. 119), this means that LO ⊆ SLO ⊆ TLO ⊆ CO. This implies that logical properties from one ontology are transitive to other ontologies (Rosen, 2012, p. 512). Other logical properties such as idempotent relation, commutative relation, associative relation, distributive relation, and structure operation (Zeng, 2002, 2004a) shall be investigated in the future specially for automated reasoning in specific system engineering analyses (INCOSE, 2004, pp. 154-178), aka ilities or specialty engineering (INCOSE, 2015, pp. 211-241).

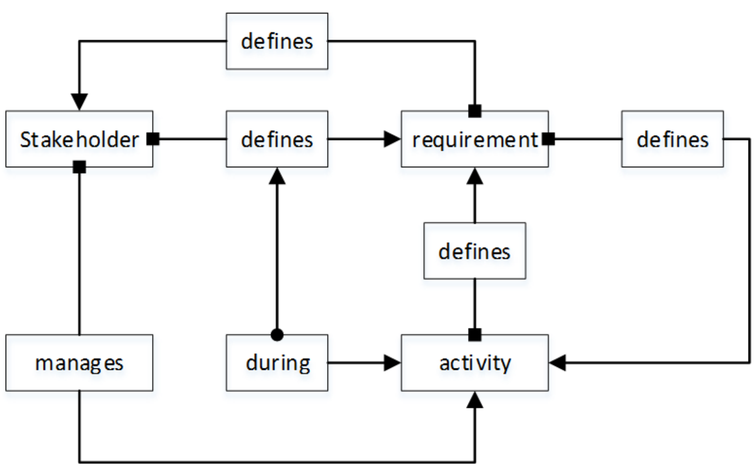

Fig. 29 The second lightest ontology

4.3.3.2.2 The second lightest ontology

The second lightest ontology includes three concepts: requirement, stakeholder, and activity. A ROM representation integrating the concepts is defined in Fig. 29. The ROM representation is an expression of the second lightest ontology. The ROM representation is created based on the interpretation and knowledge of the author of this thesis.

Table 13 List of statements in the second lightest ontology

#	Statement and relationships (red) – Necessary (N) and sufficient (S) conditions	Source of relationship in list in Appendix A (Section A.4.2)
1	Stakeholder defines requirement during activity (N). Requirement defines activity (S). Activity defines requirement (S). Requirement defines stakeholder (S).	5 5 5 5
2	Stakeholder manages activities (N). Activity defines requirements (S). Requirement defines activity (S). Requirement defines stakeholder (S).	76 5 5 5
3	Requirement defines activities (N). Activity defines requirement (S).	5 5
4	Activity defines requirement (N). Requirement defines activity (S).	5 5

The three concepts are integrated based on recursively dependent logic. This logic was previously introduced in the context of the lightest ontology. Sentence patterns were also previously discussed in the context of the lightest ontology. Based on those patterns, the statements in Table 13 are defined from the ontology in Fig. 29. Zeng (2008) discusses further details about such patterns.

4.3.3.2.3 The third lightest ontology

The third lightest ontology includes 12 concepts: requirement, stakeholder, activity, customer, interface, organization, process, project, service, system, system element, and user. A ROM representation integrating the concepts is defined in Fig. 30. The ROM representation is an expression of the second lightest ontology. The ROM representation is created based on the interpretation and knowledge of the author of this thesis.

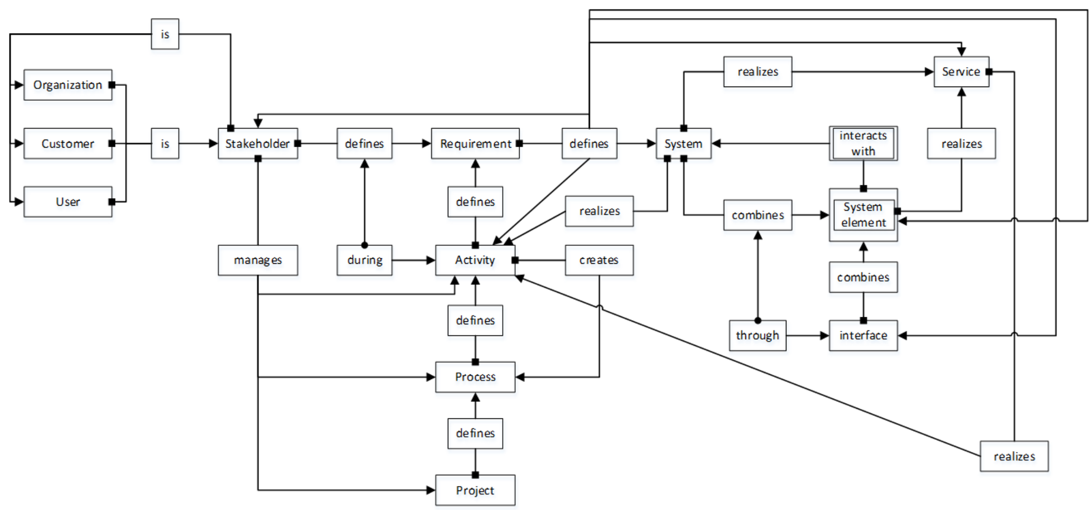

Fig. 30 The third lightest ontology

The 12 concepts are integrated based on recursively dependent logic. This logic was previously introduced in the context of the lightest ontology. Sentence patterns were also previously discussed in the context of the lightest ontology. Based on those patterns, the statements from Fig. 30 can be obtained. Considering the patterns, the statements are presented in Appendix C.

4.3.3.2.4 The proposed core ontology

The least light ontology (i.e., the proposed core ontology) includes all the concepts in Table 10. A ROM representation integrating the concepts is defined in Fig. 31. The ROM representation is an expression of the third lightest ontology. The ROM representation is created based on the interpretation and knowledge of the author of this thesis.

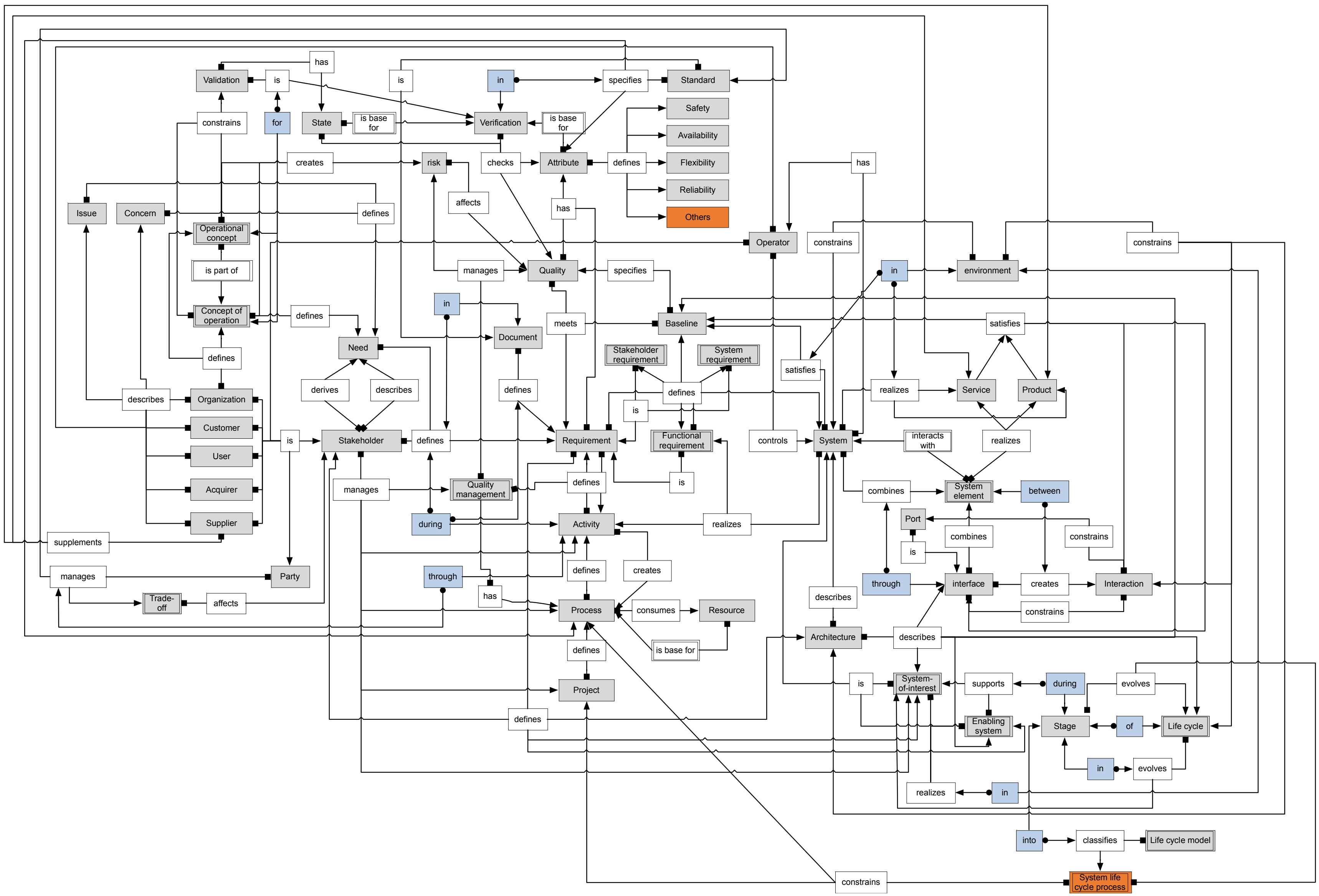

Fig. 31 The proposed core ontology

In order to make the ontology in the ROM representation more readable, one modification is made to the original constructs and conventions in a ROM representation (Zeng, 2008). The modification is the introduction of colors. Gray objects represent concepts (i.e., nouns). White (non-color) objects represent relationships (i.e., verbs). Blue objects represent prepositions. Orange objects are two additional objects to the 50 core concepts in Table 10. Each additional concept has a reason. The first additional concept (i.e., system life cycle process) was added to include one main concept of this research to the core 50 concepts in proposed core ontology. The second additional concept is to complete the list of identified attributes by including the concept other ilities (e.g., producibility, transportability, maintainability, sustainability, etc.). These ilities are defined as product and service characteristics (Hoyle, 2001, p. 29).

The concepts in the ROM representation in Fig. 31 are integrated using 24 types of relationships. Each type of relationships may appear one or more times in Fig. 31. The 24 type of relationships and their frequency in Fig. 31 are summarized in Fig. 32.

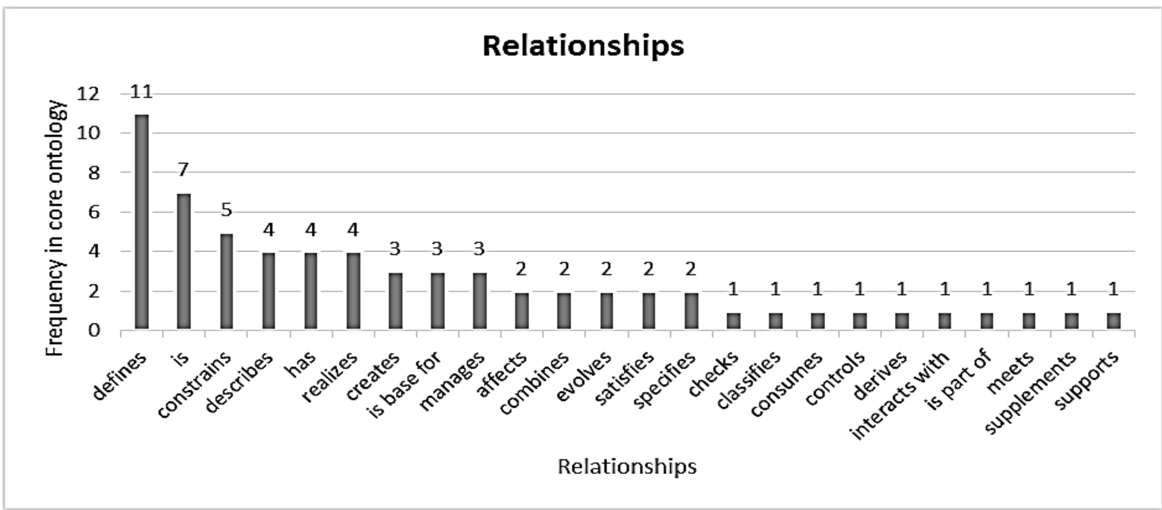

Fig. 32 Types of relationships and their frequency used for integrating the concepts in Fig. 31

The core concepts are integrated based on recursively dependent logic. This logic was previously introduced in the context of the lightest ontology. Sentence patterns were also previously discussed in the context of the lightest ontology. Based on those patterns, the statements from Fig. 31 can be obtained. Considering the patterns, the statements are presented in Appendix C.

4.3.4 Step 8.4: Test for applications

The ontology needs to be evaluated for the particular purpose that it has been developed (Ahmed et al., 2007). The purpose of this ontology is to overcome communication challenges existing in designing multidisciplinary complex products. Thus, this ontology is for people's communication purposes in the domain of requirements and system life cycle processes.

In order to overcome communication challenges, concepts from different ontologies and international standards have been identified. These concepts have also been integrated into different ontologies using relationships extracted from the investigated ontologies. Integration of concepts and relationships into ontologies was performed using ROM representations. Building the ontology constructively from previous efforts, international standards and using ROM representations is assumed to be the most effective approach to overcome communication challenges and create a shared conceptualization. This approach is expected to satisfy the set of requirements specified in step 4, step 5, and step 6 in Section 4.2.4, Section 4.2.5, and Section 4.2.6 respectively; except for validation through case studies. Validation through case studies is presented in the subsequent chapters of the thesis; but, the remaining of this section discusses how the ontology addresses the non-functional and functional requirements.

4.3.4.1 Non-functional requirements

Non-functional requirements include: 1) the ontology shall be based on peer-reviewed publications with relevant ontologies, 2) the ontology shall be based on standards with relevant terminology, 3) the ontology shall be based on external work (i.e., design theory and case studies), 4) the ontology shall be written in ROM using English, and 5) the ontology shall have the characteristics of a good ontology as concluded in the literature review section.

The first non-functional requirement states that the ontology shall be based on peer-reviewed publications with relevant ontologies. This requirement is met considering that three research groups discussing ontologies were identified. Concepts and relationships for the ontologies were extracted constructively from the three research groups.

Table 14 EBD root concepts and concepts in the proposed core ontology

EBD root concepts	Concepts in the proposed core ontology	(# of concepts	Relative frequency (# of concepts/52)
Natural environment	Environment[28], Interaction, Risk, Safety, State, Validation, Verification	7	13.46%
Built environment	Architecture, Attribute, Availability, Baseline, Concept of operations, Concern, Document, Enabling system, Flexibility, Functional requirement, Interface, Issue, Need, Operational concept, Others, Port, Product, Project, Quality, Reliability, Requirement, Resource, Service, Stakeholder requirement, Standard, System, System element, System requirement, System-of-interest, Trade-off	29	57.69%
Human environment	Acquirer, Customer, Operator, Organization, Party, Stakeholder, Supplier, User	8	15.38%
Design process	Activity, Process, Quality management	3	5.77%
Life cycle	Life cycle, Life cycle model, Stage, System life cycle processes	4	7.69%

The second non-functional requirement states that the ontology shall be based on standards with relevant terminology. The most recent editions of two international standards in the scope of the ontology were identified and investigated. The first international standard (i.e., ISO/IEC/IEEE 15288:2015, titled *Systems and software engineering - System life cycle processes*) is the most widely adopted standard in the context of system life cycle processes. This standard has been adopted as the base for developing the *Systems engineering handbook: a guide for system life cycle processes and activities* by INCOSE (2015)[29]. The second standard is ISO/IEC/IEEE 29148:2011 (titled *Systems and software engineering - Life cycle processes - Requirements engineering*). This

[28] Considering that concepts for the built and human environment are defined in the table, the term in this case is left for representing the natural environment. However, natural, built and human environment can conform the semantic meaning of the term in the proposed core ontology.
[29] INCOSE stands for *International Council on Systems Engineering* (INCOSE, 2018).

standard is defined as the current significant systems engineering standards and guides in the context of requirements by INCOSE (2015, p. 13). As a consequence, ISO/IEC/IEEE 29148:2011 is also assumed to be a widely adopted standard in the context of requirements.

The third non-functional requirement states that the ontology shall be based on external work (i.e., design theory and case studies). The ontology was built considering the underlying root concepts in EBD theory. The root concepts are: environments (natural, human, and built), process, and life cycle. The remaining part to satisfy this requirement is to evaluate the ontology in case studies based on these root concepts. These case studies are presented in the remaining chapters of this thesis. The case studies are: 1) Total Quality Management System Guideline Development Using Environment-Based Design for Area Development Planning, 2) Designing the Right Framework for Healthcare Decision Support, and 3) Integrating learning through design methodologies in aircraft design. The data analysis sections in each case study will discuss explicitly the role of root concepts in EBD and the concepts in the proposed core ontology. The concepts in the proposed core ontology are associated to the root concepts in EBD theory in Table 14. The concepts in the table are associated based on the author's knowledge. Some associations of the concepts in the table can correspond arguably to a different category. Based on the associations in the table, 13.73% of concepts corresponds to the natural environment, 56.86% of concepts corresponds to the built environment, 15.69% of the concepts corresponds to the human environment, 5.88% of the concepts corresponds to the design process, and 7.84% of the concepts corresponds to the life cycle. This table evidenced initial satisfaction of the third non-functional requirement.

The fourth non-functional requirement states that the ontology shall be written in ROM using English. Evidence to meet these requirements can be found in Section 4.3.3.2. In addition, each of the created ontologies defines necessary and sufficient conditions in natural language (i.e., written technical English).

The fifth non-functional requirement states that the ontology shall have the characteristics of a good ontology defined in the literature review section. These criteria have been partially met by the created ontologies. Each of the criteria is evaluated subjectively in Table 15. Based on the table, future work is needed to improve semantic clarity and semantic coherence in the created ontologies.

Table 15 Criteria to evaluate ontologies, originated in the literature review section

	Definition
Clarity	A limitation of the created ontologies is that they were created based on the author of this thesis knowledge. The created ontologies were constructed using concepts and relationships from published ontologies, but integrated based on the author's knowledge. Therefore, the created ontologies have concepts and relationships extracted from peer-reviewed ontological developments and international standards, but clarity problems may arise in the allocated connections. The created ontologies are clear about the intended semantic meaning of each concept and relationship. The semantic meaning of each concept and relationship in the created ontologies can be traced back to the original source; but, future work is needed to create intended definitions from the ontology (Oliver, Andary, & Frisch, 2009; Ruemler et al., 2016; Seppälä, Ruttenberg, & Smith, 2017). In addition, clarity is achieved by defining necessary and sufficient conditions based on the created ontologies, but further research shall be conducted in the subject especially in the context of the proposed core ontology. Necessary and sufficient conditions were documented in natural language (i.e., written technical English).
Coherence	A limitation of the created ontologies is that they were created based on the author's knowledge. Coherence was initially evaluated by the generation of necessary and sufficient conditions from the created ontologies. However, it was identified that further development in the subject needs to be conducted to evaluate coherence in the created ontologies. Coherence is the base for generating necessary and sufficient conditions. The subject of coherence becomes more complex as the number of concepts and relationships in the ontologies grow. This observation might suggest to consider formal logic to express the ontology in the future (Rauzy & Haskins, 2018).
Extensibility	The created ontologies have the property of extensibility. This is evidenced on the created ontologies, particularly shown in how all the ontologies are related recursively from the lightest to the proposed core ontology. These can be interpreted from the defined list of statement for each created ontology. As the

	ontologies extend, new relationships indicating new statements between concepts appear. The created ontologies could also be extended to include all the 501 found concepts. However, this extension may be more practical through the use of automated means to integrate the concepts and relationships into the proposed core ontology. These means shall be investigated and developed.
Minimal encoding bias	The ontology was encoded using written technical English and ROM representations. Technical English is widely known, use, and natural for people. ROM representations are simpler and more accessible to learn for human communication purposes than other identified ontology languages (i.e., UML, SysML, and OWL). ROM representations can be transformed to other languages (Wan et al., 2016; Wang et al., 2013). Using technical English, ROM representations and providing cases of transformation from ROM representations to other ontology languages are expected to minimize encoding bias.
Minimal ontological commitment	Different ontologies were created to minimize ontological commitment. Researchers can adopt the created ontologies, or they can develop the one that they want or need for their purposes using the identified concepts and relationships in this section. In addition, the created ontologies are intended to represent the domain of requirements and system life cycle processes trying to minimize the use of concepts and relationships in the context of systems (i.e., products). This intention enables researchers to extend any of the created ontologies for their particular designs of systems. The proposed core ontology incorporates some concepts related to mechatronics, so researchers working on other products can work with the second or third lightest ontologies.

4.3.4.2 Functional requirements

Functional requirements for the ontology come from different sources. The first source is the root concepts in EBD theory: environments (natural, human, and built), process, and life cycle. The second source is the objective of the thesis. The objective suggests investigating three areas: system, system life cycle processes, and requirements. Thus, as part of functional requirements, the ontology shall include total or partial elements related to the following concepts: environment (natural, human, and built), process, life cycle, system, and requirements. These concepts were associated to competency questions previously in Table 6.

Table 16 Competency questions answered from the core concepts in the ontology

		EBD theory				
		Natural environment	Built environment	Human environment	Life cycle	Design process
Criteria	What	Environment	Architecture, enabling system, functional requirement, product, project, requirement, resource, service, stakeholder requirement, system, system element, system requirement, system-of-interest	Stakeholder		
	Where	Interaction	Baseline, concept of operations, document, interface, operational concept, port, standard		Life cycle model, stage	Activity
	When	State	Attribute, trade-off		Systems life cycle processes	Process
	Who		Concern, issue, need	Acquirer, customer, operator, supplier, user		
	Why	Safety, risk, validation, verification	Availability, flexibility, quality, reliability	Organization, party	Life cycle	Quality management
	How	All potential combinations of what, where, when, who, and why. In other words, all potential combinations of environments (natural, built, and human), life cycle, and design process.				

Based on the context previously defined in Table 6, Table 16 relates the core concepts in the ontology (see Table 14) to the requested concepts and the competency questions. The terms are associated based on the author's knowledge; thus, different people may have a different interpretation. The terms were allocated based on guidance from the literature: 1) *ANSI/AIAA G-*

043A-2012: Guide to the Preparation of Operational Concept Documents (ANSI/AIAA, 2012, p. 19), and Appendix F (page F-17) of the *FAA System Safety Handbook* (Federal Aviation Administration, 2013). Table 16 evidenced that the ontology meets the defined functional requirement.

4.3.5 Step 8.5: Build thesaurus of terms

A thesaurus is a networked collection of vocabulary terms each of which is described with associative relations and hierarchical descriptions (Ahmed et al., 2007). A vocabulary term in this thesis is a concept or a relationship in the ontology. The semantic meaning to the vocabulary term can be found tracing back to the source from where the termed was retrieved. Associations and hierarchical descriptions can be extracted and understood directly from the ontology (i.e., ROM representations). In general, verb phrases using the verbs "*is*" or "*has*" may imply hierarchy between concepts in the ROM representations. The rest of verbs used in verb phrases may imply association relations between concepts.

However, future work is needed to create intended definitions conforming the thesaurus of terms. These definitions may employ guidance and discussions in the context of ontology (Seppälä et al., 2017), MBSE (Hartman & Zahner, 2017; Oliver et al., 2009; Ruemler et al., 2016) or general terminology work (Pavel & Nolet, 2001).

4.4 Conflict identification

A conflict refers to insufficient resources for an object to produce a desired action on its environment or to accommodate the object's action on its environment (Zeng, 2015). Conflict identification happened implicitly in Section 4.3 (i.e., environment analysis). In fact, several iterations of conflict identification were performed.

First, EBD theory and methodology were employed to analyze the general requirements of the ontology. EBD theory served to define functional requirements. EBD theory served to select the investigated ontologies. EBD methodology served to integrate environment analysis to the employed steps (1-8). The steps implied requirements to be fulfilled within each step as well as to keep track of input-output relationships between steps. These requirements are implied in the specifications suggested by Suárez-Figueroa et al. (2009) and Ahmed et al. (2007). These requirements served to evaluate the created ontologies until the current state of satisfaction was achieved.

Second, EBD theory served to identify the life cycle of the ontology. An ontology as an information product has a life cycle. Today, researchers and organizations do not agree about the life cycle of an ontology (Neuhaus et al., 2014). The created ontologies in this thesis are in the initial stage of development; therefore, the current purpose is for human communication and understanding. The created ontologies serve to communicate the context of the ontology and the ontology design process. As a result, downstream life cycle requirements (e.g., costing, implementation, computational testing, maintenance, and retirement) for the ontology were omitted at this point. This decision is part of conflict identification.

Third, vocabulary disagreements exist in the investigated scope of the ontology. Vocabulary disagreements were addressed building constructively from different peer-reviewed ontological developments. Vocabulary disagreements were also harmonized using international standards and a formal, explicit specification through ROM. Vocabulary disagreements and provided solutions can be implied from Step 8.2: Identify existing taxonomies and Step 8.3: Create taxonomies (ontologies).

Fourth, conflict identification happened in testing the ontology for application in Section 4.3.4. Based on this section, improvements to meet non-functional requirements are needed. In particular, needed improvements were identified for two criteria: clarity and coherence. Needed improvements are described in Table 15.

4.5 Solution generation

The development of the proposed ontologies is in the initial stage. According to Fig. 33, the initial stage can be interpreted as requirement development, ontological analysis, and ontology design. Final stage can be system design, ontology development & reuse, deployment, and operation & maintenance. To move from this initial stage to the final stage, conflicts in Section 4.4 shall be solved systematically. This movement is called solution generation (Zeng, 2015).

Fig. 33 An ontology life cycle model (Neuhaus et al., 2014, p. 57)

At the initial stage, solution generation is still needed for the identified conflicts. At this stage, a joint evaluation involving other researchers is needed for each of the previous discussed iterations of conflict identification. The evaluation may help to refine and improve the design process presented in this chapter. The evaluation may also help to discover other requirements. Solution generation will be needed to address any identified refinement, improvement, and new requirements.

In addition, solution generation is needed to address specific conflicts (i.e., limitations) defined in Table 15. Based on these limitations, solution generation is also needed to develop specific guidance to analyze system life cycle processes using the ontology (INCOSE, 2004, pp. 154-178; 2015, pp. 211-241). At this stage of progress, the ontology may be considered as a reference model[30] of the current state of understanding in the context of requirements and systems life cycle processes. Fig. 14 defines a reference model (i.e., ontology) as the output of the descriptive study stage in the DRM framework. INCOSE (2004, pp. 154-178; 2015, pp. 211-241) define specific types of guidance that could be developed using the ontology. Developing specific guidance to analyze system life cycle processes corresponds to the prescriptive study stage in the DRM framework in Fig. 14. Blessing and Chakrabarti (2009, pp. 34, 141-143) state that guidance (i.e., design guideline) is a type of support to be developed in the prescriptive study stage of the DRM framework. Design guidelines for requirements engineering may include: 1) developing & managing the characteristics of well-formed requirements, 2) developing & managing the

[30] A reference model represents the existing situation in design and is the reference against which situation intended improvements are benchmarked (Blessing & Chakrabarti, 2009, p. 20).

characteristics of well-formed set of requirements (i.e., specifications) (ISO/IEC/IEEE, 2011). Design guidelines are planned to be investigated considering the idea of questions asking and answering in EBD (Zeng, 2015).

Solution generation is also needed to address the requirements of the final stage of the ontology. This work has not been initiated yet. Neuhaus et al. (2014, pp. 50-70) proposed requirements to be addressed at each stage of the ontology life cycle model in Fig. 33.

Finally, costing of ontologies has not been investigated. As a product, ontologies shall have a cost. Solution generation may address future investigation in costing ontologies.

4.6 Conclusions

The objective of this chapter is to *"propose a requirements ontology to guide the analysis of system life cycle processes".* To meet this objective, this chapter followed a step-by-step ontology design process to propose the desired ontology. Ontology design involved defining requirements for the ontology, and executing environment analysis, conflict identification, & solution generation. *To propose a requirements ontology to guide the analysis of system life cycle processes* is a complex task that considers different aspects of the natural, built, & human environment, design process, and life cycle perspective. However, to make the proposed core ontology more accessible and understandable for different users, lightest versions were also proposed in this chapter. The lightest ontology deals only with the two most important concepts in the domain of requirements. The second lightest ontology deals mainly with requirements and management process. The third lightest ontology deals with requirements, management process, and general concepts related to the built environment. The proposed core ontology expands each of the previous ontology specially to cover requirements and system life cycle processes in the engineering domain of mechatronic products. The lightest ontologies are different versions of the MIM.

EBD theory and methodology were the foundation to validate the requirements ontology and right semantics. Data collection mainly happened in environment analysis. In contrast to data collection, data analysis covered the three activities in EBD methodology. Different sections related to data analysis such as test for application, build thesaurus, conflict identification, and solution generation define specific limitations and future work needed to evolve the proposed ontology.

Finally, the proposed ontology is expected to be an initial model for communication and understanding in multidisciplinary design projects. Teams may use the ontology to create a shared understanding of the context of requirements for system life cycle processes at any stage of a design project. Concepts and relationships in the ontology form a common vocabulary of the context. Effective communication of requirements requires a common vocabulary, where the ontology serves as kind of knowledge representation (Kendell & Jenkins, 2010). The ontology can help teams to define specific vocabulary and requirements in their domain of interest. Specific vocabulary and requirements may involve extending the ontology with concepts particular to a domain of interest. For example, the concept "system of interest" in Fig. 31 can be extended/replaced with civil airplane. Accordingly, the rest of concepts in the ontology may be extended/replaced in the context of a civil airplane. Other extensions can explore to include other concepts from the investigated research efforts. The relationships in the ontology may suggest how to develop and manage logically requirements during the design process. This development is an initial stage, so further research in design guidelines is needed.

Chapter 5: Case study 1 - Total quality management system guideline development using Environment-Based Design for area development planning

5.1 Introduction

The contribution of this chapter is to validate the proposed core ontology in Chapter 4. To achieve the needed validation, this chapter employs a case study titled *TQMS for land development in City of Edmonton* as a source of content analysis to facilitate retrospection. The objective of this case study was to *"Develop a Total Quality Management System guideline for Area Development Planning sub-section of the Drainage Planning section, Drainage Services, City of Edmonton"*. The chapter corresponds to *TQMS for land development in City of Edmonton* highlighted in Fig. 22.

To validate the proposed ontology, the rest of the chapter is organized as follows. Section 5.2 describes a general background in the context of project. Section 5.3 presents data collection using EBD methodology. Section 5.4 presents data analysis and discusses the findings. To synthesize the analysis and findings, Section 5.5 concludes about the proposed core ontology and its role in land development projects.

5.2 General background

This section has the goal of depicting a general overview about the context of the project. To achieve the goal, this section is organized as follows. Section 5.2.1 describes area development planning. Section defines the context of total quality management system and a guideline. Section 5.2.3 contextualizes and justifies the adoption of EBD to execute the project.

5.2.1 Area development planning

Land development is a complex endeavour. Land development in general performs three major actions: planning, engineering, and surveying. These actions can be conducted following a generic design process. The generic land development process can follow activities such as 1) feasibility and site analysis, 2) conceptual design, 3) schematic design, 4) final design, 5) plan submission and permitting, and 6) construction. The generic development process and specific deliverables are defined in Table 17 and Table 18. A high-level generic alternative view of the land process development process in Table 17 and Table 18 is presented in Fig. 34.

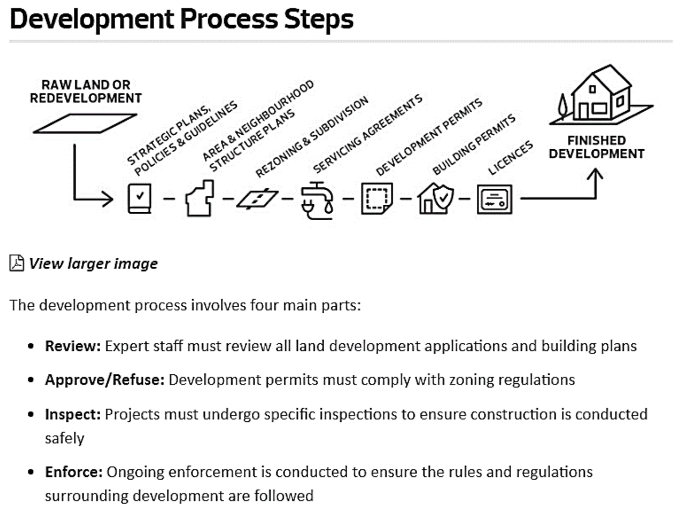

Fig. 34 Urban planning and design development process (City of Edmonton, 2018)

Table 17 A generic land development process: activities and deliverables – constructed from The Dewberry Companies (2002)

Activities	deliverables
Feasibility and site analysis	Comprehensive planning and zoning Site plan ordinances, subdivision regulations, and building codes Exactions, infrastructure enhancements, and fees Real property law Engineering feasibility Environmental regulations Environmental site assessment Historic and archaeologic assessment Market analysis and economic feasibility The rezoning process
Conceptual design	Development patterns and principles

Table 18 A generic land development process: activities and deliverables – constructed from The Dewberry Companies (2002) (Continued Table 17)

Schematic design	Boundary surveys for land development Control surveys Topographic surveys Preliminary engineering Environmental and natural resources Historic preservation and archeology Environmental considerations
Final design	Suburban street design Storm drain design Design of stormwater management facilities Floodplain studies Grading and earthwork Wastewater collection Water distribution Wastewater treatment Water supply and treatment Erosion and sediment control Contract documents and specifications Construction cost estimating
Plan submission and permitting	Subdivision submittals Plan submittal, review, and approval process Environmental permits
Construction	Construction stakeout surveys Building permits and certificates of occupancy

Area Development Planning is a component of land development. The Area Development Planning (ADP), sub-section of the Drainage Planning, was created in November 2012 as part of the Drainage Planning section re-organization. The ADP's mandate is developing and implementing initiatives and strategies to provide sustainable drainage infrastructure for the land development in City of Edmonton so that the public safety (flood prevention) and health (stormwater quality control) are protected.

The ADP sub-section consists of three groups: Drainage Master Plan, Flood Prevention and erosion control, and stormwater quality management. Drainage Master Plan group is responsible for developing, reviewing and approving drainage master plan, watershed management plan, and area structural plan, as well as land development applications and amendment. Flood Prevention and erosion control group is responsible for developing city-wide flood prevention projects in both proactive and reactive approaches. The proactive approaches include utilization of school surplus sites as space for stormwater management facilities for mature neighborhoods, wetland acquisition plan to integrate natural wetland conservation into stormwater management strategy, creek erosion and sediment control. The reactive plans are those dealing with flooding from extreme storm events. The stormwater quality management group is responsible for researching and developing innovative technologies to improve stormwater quality, with a focus on promoting green infrastructure (Low Impact Development).

Due to the complexity of land development process, the role of drainage planning, in particular the integrated stormwater management, has been very challenging both politically and technically. To provide efficient, effective, and high-quality services to land development customers as well as protect the interests of citizens require a clean and well-defined quality management system, which will be the goal of this research.

5.2.2 Total quality management system: a guideline

Quality, or lack of quality, affects an entire organization from supplier to customer and from product design to maintenance (Heizer, Render, & Griffin, 2014, p. 191). Thus, quality may affect organization reputation, product liability, and global implications (Heizer et al., 2014, p. 192).
International standards have been created in the context of quality and quality management systems. ISO international standards have been recognized and adopted internationally in the context of management systems (ISO, 2018b). The two most widely adopted international standards, measured as number of certificates, related to management systems are ISO 9000 and ISO 14000 (ISO, 2017). The focus of ISO 9000 is to establish quality management procedures through leadership, detailed documentation, work instructions, and record keeping (Heizer et al., 2014, p. 194). It is important to note that the procedures say nothing about the actual quality of a

product, thus, they deal entirely with standards to be followed (Heizer et al., 2014, p. 194). Indeed, ISO 9000 is a family with four core standards: 1) ISO 9000 (Quality Management Systems – Fundamentals and Vocabulary), 2) ISO 9001 (Quality Management Systems – Requirements), ISO 9004 (Quality Management Systems – Guidelines for performance improvement), and ISO 19011 (Guidelines for auditing management systems) (Hoyle, 2018, pp. 55-58; ISO, 2016). In complement to ISO 9000, ISO 14000 is also a series of environmental management standards (ISO, 2009). The overall aim of ISO 14000 is to support environmental protection and prevention of pollution[31] in balance with sociotechnical needs (Goetsch & Davis, 2001, p. 7). ISO 14000 contains 5 core elements: 1) environmental management (ISO 14001), 2) auditing (ISO 19011), 3) performance evaluation (ISO 14031), 4) labelling (ISO 14020), and 5) life cycle assessment (ISO 14040) (Heizer et al., 2014, p. 194). Safety management systems (SMS) have also been considered a third block in quality management systems besides ISO 9000 and ISO 14000 (Goetsch, 2011, pp. 189-190, 648-692; Hoyle, 2001, pp. 3-6), but it was not part of ISO international standards (Griffith, Stephenson, & Bhutto, 2005; Jørgensen, Remmen, & Mellado, 2006; Rebelo, Santos, & Silva, 2016). A health and safety program is a plan of action designed to prevent injuries and illness at work (Canadian Centre for Occupational Health and Safety, 2018). This year, ISO published the first edition of the international standard ISO 45001:2018 related to occupational health and safety management (i.e., SMS) to achieve integration between ISO 9000, ISO 14000, and SMS (ISO, 2018a). Although both ISO 14000 and ISO 45001 affect the context of operation of ADP, the scope of this case study is limited to ISO 9000 specially ISO 9001:2008 (ISO, 2008a). ISO 9001 is directly aligned with to total quality management (Goetsch & Davis, 2014, pp. 246-254). Total quality management can be the foundation to integrate ISO 9001, ISO 14000 and ISO 45000 in the future into what is called an integrated management system (Jørgensen et al., 2006; Rebelo et al., 2016).

To understand the scope of total quality management system, the meaning of the concept shall be broken down into its constituent components. The components are: system, management, management system, quality management, quality management system, and total quality management. All the concepts except total quality management (TQM) are defined in Table 19.

[31] Negative environmental aspects of pollution include but are not limited to emissions to the atmosphere, discharges to water or soil, generation of waste, use of natural resources, community impact, and generation of noise, dust, odors, etc. (Goetsch & Davis, 2001, p. 18).

Total quality management refers to quality emphasis that encompasses an entire organization, from supplier to customer (Heizer et al., 2014, p. 195). TQM stresses management commitment to have a continuing companywide drive toward excellence in all aspects of products and services that are important to customers. TQM requires a never-ending process of continuous improvement that covers people, equipment, suppliers, materials, and procedures. The basis of TQM philosophy is that every aspect of an operation (process) can be improved. The meaning of total quality management system (TQMS) can be composed integrated the meaning of these components. Thus, *TQMS is the management to direct and control an organization with regard to quality that encompasses all aspects of products and services that are important to all parties in an entire organization from supplier to customer.*

Table 19 Definitions of concepts related to total quality management system (ISO, 2005) [32]

Concept	Definition	Source
System	Set of interrelated or interacting elements.	ISO (2005)
Management	Coordinated activities to direct and control an organization.	ISO (2005)
Management system	System to establish policy and objectives and to achieve those objectives.	ISO (2005)
Quality	Degree to which a set of inherent characteristics fulfils requirements.	ISO (2005)
Quality management	Coordinated activities to direct and control an organization with regard to quality.	ISO (2005)
Quality management system (QMS)	Management system to direct and control an organization with regard to quality.	ISO (2005)

The objective of the case study is to "Develop a Total Quality Management System guideline for Area Development Planning sub-section of the Drainage Planning section, Drainage Services, City of Edmonton". The objective defines to develop a guideline. A guideline is defined as "an official recommendation or advice that indicates policies, standards, or procedures of how something should be accomplished" (ISO/IEC/IEEE, 2017). In the context of the case study, a

[32] That version of the standard was utilized during the project. ISO (2015a) is the most up to date version of the international standard.

guideline means recommendation or advice indicating procedures[33] to implement a TQMS for Area Development Planning (i.e., Drainage Master Plan, Flood Prevention and erosion control, and stormwater quality management).

5.2.3 Contextualizing Environment-based design (EBD) methodology in total quality management systems

EBD theory was introduced in the research methodology chapter. EBD theory described in the research methodology has the right components to describe the context of TQMS. In general, Fig. 35 depicts the concept of TQMS using EBD theory. *E* in the figure stands for environment: natural, built, and human. The environment shall be defined for each component and relationships in the figure. Naturally, inputs and outputs are defined using the environment. Life cycle covers the evolution of a system through processes in an entire organization from customer to supplier. Each process defined as SIPOC shall have at least one accountable representative from the supplier and customer. The generic model in the figure describes that the logic in the model extends until the process *n* implied in $SIPOC_n$. Generally, the process $SIPOC_1$ may refer to business and mission analysis process, while SIPOC*n* may refer until the disposal process at the end life of the product or service; where both processes corresponds to technical processes by ISO/IEC/IEEE (2015). The output from the process in one SIPOC becomes the input to the following process. This input-output relationship directs with regard to quality expressed in the form of requirements or specifications. Requirements or specifications encompass all aspects of products and services. Requirements and specifications enable to control an organization with regard to quality, where quality is the degree to which a set of inherent characteristics fulfills requirements. Finally, the model[34] implies all the relations in ATDM including the transitive relation to express causality (Zeng, 2002, 2004a).

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[33] Procedures is an information item that presents an ordered series of steps to perform a process, activity, or task (ISO/IEC/IEEE, 2017).

[34] The model in Fig. 35 is represented as linear and sequential to deliver effectively the idea, but it can be adapted to any type of life cycle model.

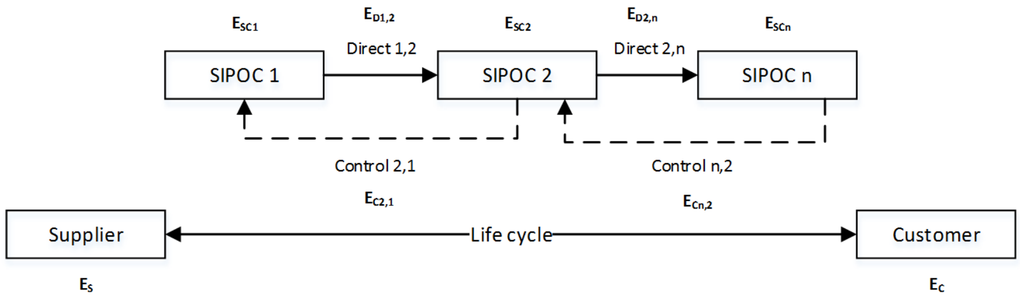

Fig. 35 TQMS model in terms of EBD theory and SIPOC diagram

The TQMS model in terms of EBD theory in Fig. 35 expands the view of traditional SIPOC diagrams. For example, Fig. 36 is the representation of a process expressed in SIPOC diagram view. In general, Fig. 36 implicitly defines requirements (i.e., specifications) among other inputs to a process in order to create a product, service, information, or paperwork that satisfies the requirement. In particular, Fig. 36 fails to relate different processes. In addition, Fig. 36 fails to introduce completeness defined by life cycle. Those failures from Fig. 36 are addressed in Fig. 35. The elements defined as input and output in Fig. 36 can be classified in term of the environment as shown in Table 20. Table 20 also classifies three alternative frameworks: ISO (2008a), ISO (2015b), and NIST (2015). Therefore, Table 20 confirms that EBD is effective to represent SIPOC diagrams and related elements. Thus, EBD theory is effective to represent TQMS as also evidenced in Fig. 35.

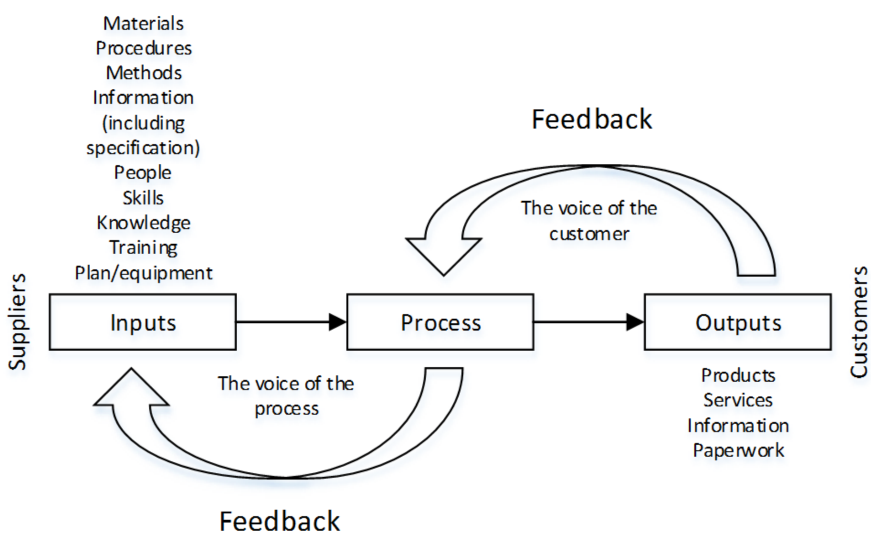

Fig. 36 A process expressed in SIPOC diagram view (Oakland, 2003, p. 12)

Table 20 Categorization of alternative frameworks into environment components in EBD theory

Environment	Input	Source
Natural	x	Fig. 36
	x	ISO (2008a)
	Inputs & outputs (matter and energy)	ISO (2015b)
	x	NIST (2015)
Built	Inputs (materials, procedures, methods, information including specifications, skills, knowledge, training, plant/equipment), Process, Output (products, services, information, paperwork), Voice of the customer (feedback), Voice of the process (feedback)	Fig. 36
	Inputs (information flow, e.g., customer requirements), Value-adding activities (management responsibility, resource management, product realization, and measurement, improvement & analysis), Output (product), Customer satisfaction, Continual improvement of QMS	ISO (2008a)
	Organization context, Leadership, Inputs (materials, resources, or information e.g., needs, expectations, or requirements), Activities (planning, support, operation, monitoring & measurement – e.g., performance evaluation, and improvement), Outputs (product, service, or decision), Customer satisfaction	ISO (2015b)
	Core values, Concepts, Leadership, Strategy, Operations, Results, Measurement, Analysis, Knowledge management, Integration	NIST (2015)
Human	Suppliers, People, Customers	Fig. 36
	Customers	ISO (2008a)
	Customers (internal and external), Interested parties	ISO (2015b)
	Customer, workforce	NIST (2015)

EBD theory is the foundation of EBD methodology (Zeng, 2011, 2015). For this case study, the prescriptive EBD (aka as EBD methodology) was employed as the development methodology. EBD methodology includes three activities: environment analysis, conflict identification, and solution generation (Zeng, 2015). Environment analysis defines the current environment system. Conflict identification identifies undesired conflicts between environment relationships. Solution generation generates a design (e.g., service, product, process, or system) by resolving a group of chosen conflicts. The three activities work together to update the environment and its internal relationships to solve a design problem. The design process continues with new environment analysis until no more undesired conflicts exists.

The activities suggested in EBD methodology are effective to create a guideline to implement a TQMS. The activities are effective compared to alternative suggested implementations. One alternative implementation guideline is the process approach in ISO 9001:2015 (ISO, Not specified). A second alternative approach is the guidelines for implementing ISO 9000 quality management systems in public sector organizations by the Canadian General Standards Board (2002). Activities in EBD methodology and alternative implementations are compared in Table 21. Based on the table, alternative 1 expands in environment analysis while alternative 2 extends in solution generation. Considering EBD philosophy, all of them are important, but conflict identification shall be driving force of the design endeavour. The purpose of this comparison was to validate that EBD methodology is effective to conduct this case study. The thinking through EBD methodology for this case study is summarized in Fig. 37.

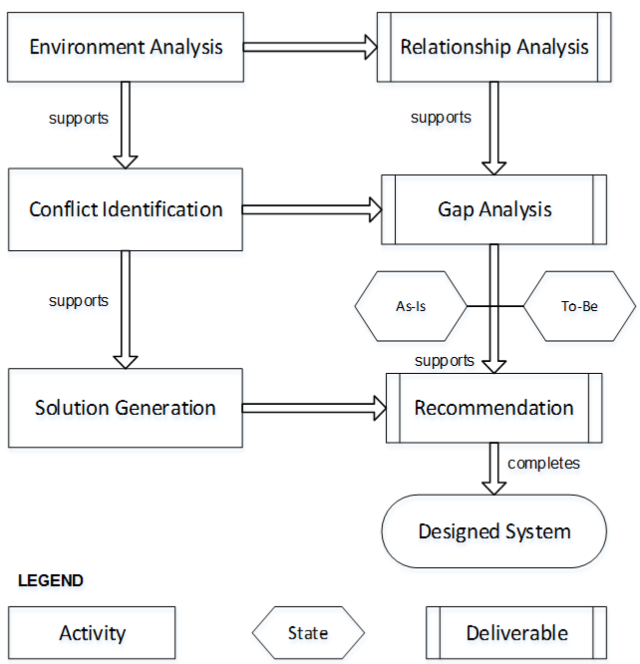

Fig. 37 EBD methodology: activities and deliverables

Table 21 EBD methodology compared to alternative implementation guidelines

Activities	Alternative 1	Alternative 2
Environment analysis	Define the context of the organization Define the scope, objectives and policies of the organization Determine the processes in the organization Determine the sequence of the processes Define people or remits who take process ownership and accountability Define the need for documented information Define the interfaces, risks and activities within the process Define the monitoring and measurement requirements Define the resources (e.g., human resources, infrastructure, environment, information, knowledge, natural resources, materials, and financial resources) needed	Prepare foundation
Conflict identification	Verify the process against its planned objectives	Conduct a gap analysis Conduct QMS reviews Assess QMS by a third party
Solution generation	Implement Improve	Secure management commitment Establish a preliminary implementation plan Finalize implementation plan Address the gap (implementation) Celebrate the successful QMS implementation Sustain and improve Celebrate successful sustainability

5.3 Data collection: Environment-based design (EBD) methodology

This thesis started data collection in a collaborative research project with the section of Area Development Planning at City of Edmonton, Alberta, Canada. The project lasted 6 months from June to December in 2013. The main objective of the project was to create a guideline to develop a total quality management system for Area Development Planning. During the project, informal interviews help to clarify/understand the scope and objective of the project. After the interviews, questionnaires were created and used as data collection methods to understand workflows in the section of Area Development Planning.

In synthesis, data collection does: 1) model of the on-going business process; and 2) review ISO 9001:2008 standard. The first task of modeling the on-going business is done based on questionnaire interview. The second task is done by document reviewing and analysis. The two tasks correspond to environment analysis in Section 5.3.1. The two tasks are evaluated systematically to identify gaps between the modeled business process and the requirements in the reviewed documents. This systematic evaluation corresponds to conflict identification in Section 5.3.2. The two parts are integrated resulting in a total quality management guideline to be implemented by ADP members in compliance with ISO 9001:2008 standard. This integration corresponds to solution generation in Section 5.3.3.

5.3.1 Environment analysis

The objective of environment analysis in EBD is to identify the environment system in which a desired product is to work (Zeng, 2011). The environment system is represented using Recursive Object Model (ROM) (Wang et al., 2013). The objects, relations, symbols, and descriptions used in ROM representations follow the definitions by Zeng (2008). Procedures for building ROM representations are also defined by Zeng (2008, 2011) and Wang and Zeng (2009). Guidance to infer a product-environment system from a ROM representation is provided in the reference (Wang et al., 2013).

Fig. 38 defines that the environment analysis process starts with a design problem and finishes with an updated product-environment system. The core of environment analysis is question generation and answering. The question generation process includes two kind of questions: generic and domain specific ones (Wang & Zeng, 2009). Generic questions clarify and extend the meaning of the design problem. Domain specific questions identify hidden requirements implied in the life cycle of the product. The process in Fig. 38 stops until similar answers for the generated questions are obtained or the obtained information is enough for the designer to decide.

Following the process indicated in Fig. 38, the environment analysis for this project was carried out in 7 steps. The steps are: 1) draw a ROM representation for the objective of the case study, 2) define a product-environment system, 3) generate questions (first round of question), 4) answer the questions (first round of answer), 5) generate questions (second round of question), 6) answer the questions, and 7) update product-environment system. Steps 1 to 4 corresponds to iteration 1 (Section 5.3.1.1), and steps 5 to 7 corresponds to iteration 2 (Section 5.3.1.2).

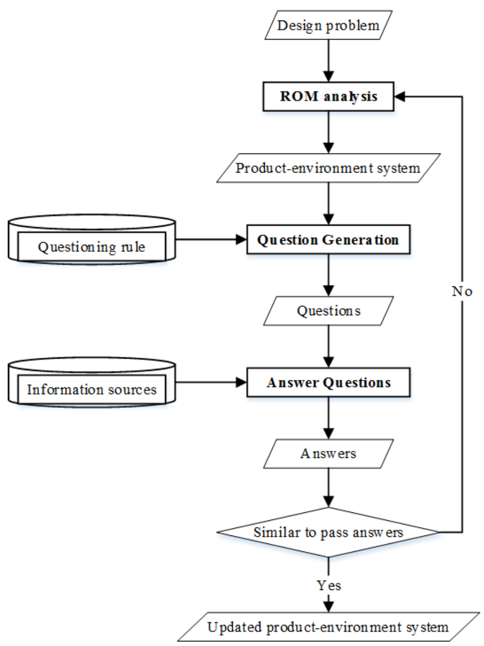

Fig. 38 Environment analysis process in EBD methodology (Wang & Zeng, 2009)

5.3.1.1 Iteration 1

Iteration 1 presents steps 1 to 4 defined in the previous section. Step 1 is to draw a ROM representation for objective of the case study. The objective is *"Develop a Total Quality Management System guideline for Area Development Planning sub-section of the Drainage Planning section, Drainage Services, City of Edmonton"*. A ROM representation for the project objective is drawn in Fig. 39. The ROM representation uses the objects, relations, symbols, and descriptions presented in Chapter 4, originally defined by Zeng (2008).

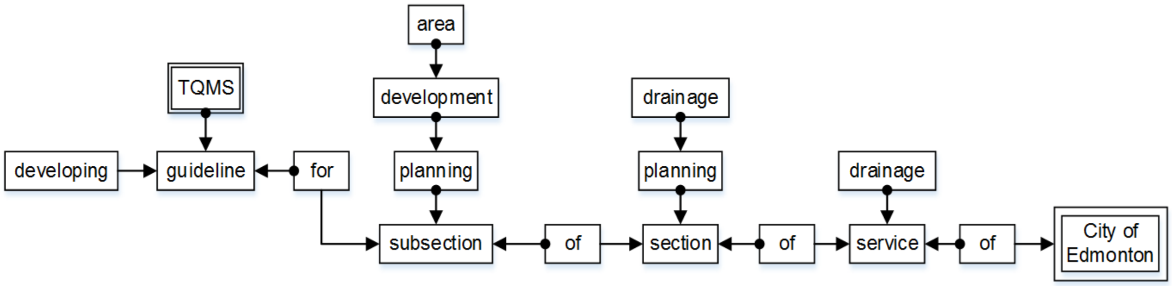

Fig. 39 ROM representation for the design problem

Table 22 Generic questions, first round of questions

#	Questions
Q1.1	Why to develop a TQMS guideline for Area Development Planning (ADP) Subsection?
Q1.2	What is drainage service of City of Edmonton?
Q1.3	What is drainage planning section?
Q1.4	What is drainage planning section of drainage service?
Q1.5	What does area mean in our project?
Q1.6	What does development mean in our project?
Q1.7	What does planning mean in our project?
Q1.8	What is ADP?
Q1.9	What is ADP subsection of drainage planning section?
Q1.10	What does ADP plan?
Q1.11	What is a TQMS guideline?

Step 2 is to define the product-environment system. A product-environment system is composed of a product, its environment components and their mutual relationships. Using the rules by Wang et al. (2013) and the ROM representation in Fig. 39, it can be implied that the product[35] is a "guideline", which is modified and constrained by "TQMS". The relevant product's environment components are "area development planning subsection", "drainage planning section", "drainage service", and "City of Edmonton". The object "planning" constraining the object "subsection" has two semantic functions. One is a noun constraining another noun, for example, TQMS guideline for area development planning subsection. The second is an

[35] Product in a product-environment system refers to what is needed to be designed.

interaction[36] between the product and its environment, for instance, TQMS guideline for planning area development. Highlighting the two semantic differences is important because each meaning leads to generate different questions (Wang & Zeng, 2009).

Step 3 is to generate questions. In the environment analysis, two kinds of questions are asked: generic and domain specific questions. These questions are generated following the rules presented by Wang and Zeng (2009). At this point in the case study, the generated questions only include generic ones for the clarification and extension of the meaning of the product-environment system. Thus, domain specific questions will be generated in iteration 2 (Section 5.3.1.2). The generated generic questions can be found in Table 22. The questions apply to the context implied in the ROM representation in Fig. 39.

Step 4 is to answer the questions. Two approaches were used to answer the questions in Table 22: to interview ADP's general supervisor (GS) and to search on the City of Edmonton website. The interview took place at the beginning phase of the case study. After the interview, answers were refined systematically during the life span of the case study. The questions and their respective answers can be found in Table 23. The answers for Q1-2 and Q1-8 were too long to be included in Table 23, so the table includes a short version of the real answer.

Table 23 Questions and answers (first round of question)

#	Questions	Answers
Q1-1	Why to develop a TQMS guideline for Area Development Planning (ADP) Subsection?	ADP wants to improve continuously the quality and efficiency of its service. The TQMS guideline should comply with the related standards, which is ISO 9001:2008 in this case.
Q1-2	What is Drainage Services of City of Edmonton?	Drainage Services Branch operates within the framework of the City Council-approved 2004-2014 Drainage Master Plan, ISO 14001 and the 10-year Approval-to-Operate (2005-2015) issued and regulated by the Province of Alberta (The City of Edmonton,

[36] The term interaction is used to represent the relationships between a product and the environment components.

		2012d). Drainage services are defined in the branch mandate, vision, mission and organizational chart. The organizational chart shows the hierarchical relationships between the City of Edmonton, Drainage Services, Drainage Planning Section and ADP Subsection.
Q1-3	What is Drainage Planning Section?	Drainage Planning provides management, planning, technical drafting, data retention, customer support and services necessary to commission, repair, upgrade, and mitigate the environmental impacts of the City's sewerage and drainage systems (The City of Edmonton, 2004).
Q1-4	What is Drainage Planning Section of Drainage Services?	The role of Drainage Planning Section in Drainage Services is to manage the long-term strategy to provide sustainable Drainage Services to the city development and residents including environment protection, especially on reducing water pollution. Drainage Planning is stewardship in protecting North Saskatoon watershed. Furthermore, Drainage Planning is responsible for developing financial management for drainage services. A hierarchical representation between Drainage Planning Section and Drainage Services is shown in Fig. 40. The hierarchical representation was created when answering question Q1-2.
Q1-5	What does area mean in our project?	In our project, the area means the Edmonton region.
Q1-6	What does development mean in our project?	In our project, the development means the process of land being developed.
Q1-7	What does planning mean in our project?	Planning is the process of thinking about and organizing the activities required to achieve a desired goal. Our planning is under Drainage Services; it belongs to Drainage Planning.

Q1-8	What is ADP?	The ADP subsection consists of three groups: Drainage planning for land development, Stormwater management and Green infrastructure & environment compliance. The groups operate under the guidance defined in ADP's operating framework, mandate, vision and mission.
Q1-9	What is ADP Subsection of Drainage Planning Section?	The role of ADP within the Drainage Planning Section is to provide the services expected from the three groups in the subsection. A hierarchical representation between ADP Subsection and Drainage Planning Section is shown in Fig. 40. The hierarchical representation was created when answering question Q1-2.
Q1-10	What does ADP plan?	ADP plans initiatives and strategies to support sustainable development in the City of Edmonton.
Q1-11	What is a TQMS guideline?	A TQMS guideline has instructions to plan area development complying with "ISO 9001:2008 requirement". The instructions shall include a work handover procedure.

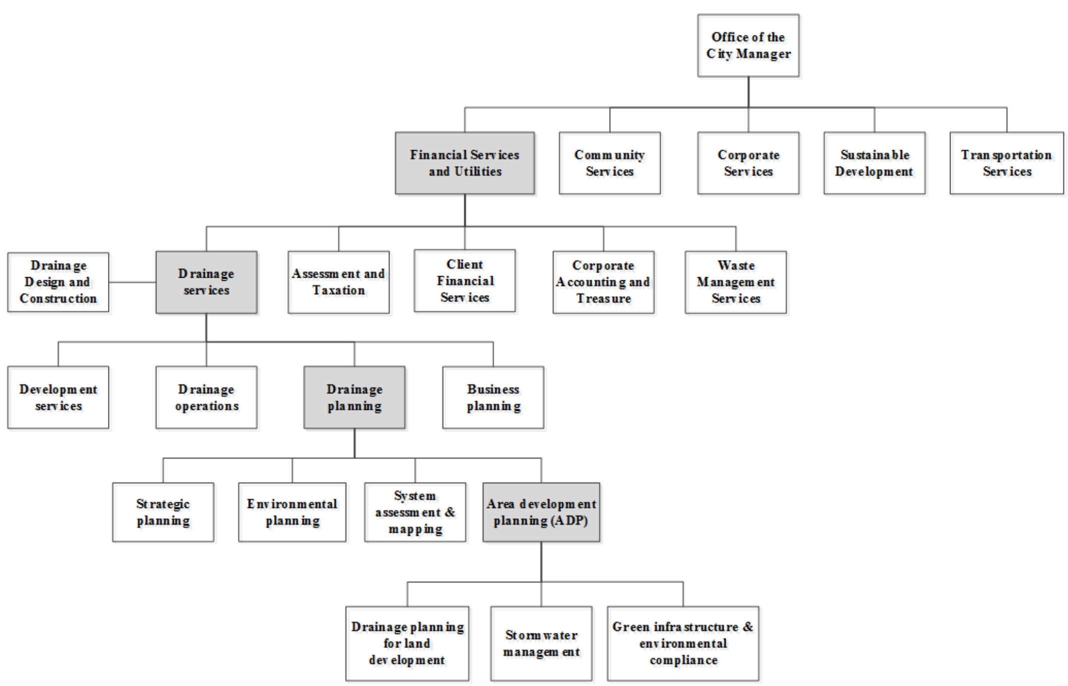

Fig. 40 Drainage Services Branch, Drainage Planning Section and ADP Subsection within the City of Edmonton organizational chart (The City of Edmonton, 2012a, 2013b)

Based on the answers to the questions in Table 23, the resulting interpreted product-environment system in ROM representation is defined in Fig. 41. This figure is the foundation to initiate iteration 2 (Section 5.3.1.2).

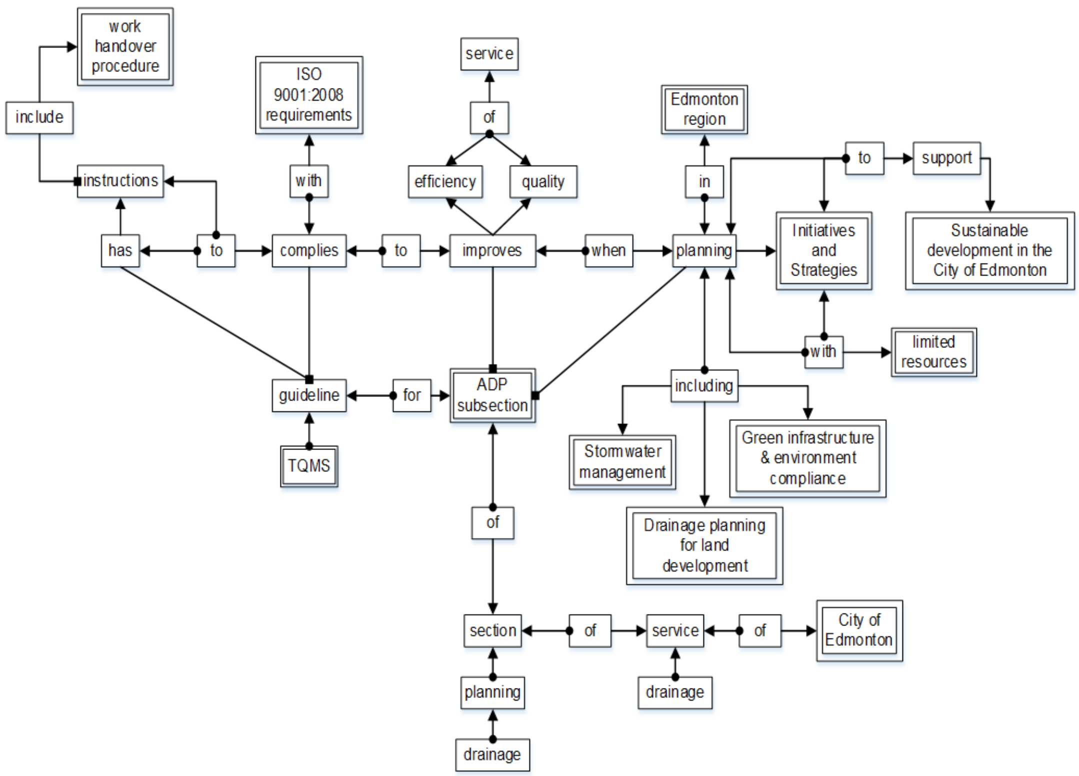

Fig. 41 Product-environment system in ROM representation after the first round of question

5.3.1.2 Iteration 2

Iteration 2 presents steps 5 to 7 defined at the end of Section 5.3.1. Step 5 is to generate questions (i.e., a second round of questions). The starting point of step 5 is the ROM representation in Fig. 41. A second round of generic questions is needed to further clarify the environment components in the product-environment system in Fig. 41. Besides generic questions, domain specific questions are also required to collect hidden requirements in other environment components. These environment components are implied in the product life cycle. Environment components related to the life cycle activities were elicited by interviewing each ADP's member and external stakeholders. Based on Fig. 41, generic questions and domain specific questions for interviewing were created following the rules by Wang and Zeng (2009). The created questions were combined and refined to optimize the interviewing time in the project. Table 24 shows the optimized questions asked to internal and external stakeholders. The questions in the table help to identify group's tasks, responsibilities, and workflows. Also, the questions help to identify information about the tasks and responsibilities for each member's position, specifying needed skills, knowledge and technologies to perform the individual group tasks. Q2-1 to Q2-4 are used to collect information about the members' group. Q2-5 to Q2-11 are used to identify information of members' position. Q2-12 to Q2-18 helps to build the relationships between ADP' members and external stakeholders. Q2-19 tries to collect information about any existing work handover procedure. Q2-20 guides to collect ISO 9001:2008 requirements. The questions in Table 24 are answered in step 6.

Table 24 Second round of questions and answers for environment analysis

For each group	Questions
Q2-1	What are the tasks and responsibilities of the group?
Q2-2	Who does the group interact with (other groups or external stakeholders)?
Q2-3	What, when, and how do these interactions happen (input and output)?
Q2-4	What kinds of positions are included in this group?
Q2-5	What are your responsibilities and tasks?
Q2-6	Who send these tasks to you?
Q2-7	When and how do you receive these tasks?
Q2-8	How do you fulfill these tasks? What knowledge, technologies, and skills do you need for each task?
Q2-9	Who do you need to contact with for each task? When and how?
Q2-10	What are the expected deliverables for each task?
Q2-11	Who do you need to send the deliverables to?
Q2-12	Could you introduce your group briefly?
Q2-13	What is the working relation between your group and ADP group?
Q2-14	Who are your main contacts in ADP? Why are they?
Q2-15	What do you receive from them and what do they want from you?
Q2-16	What do you send to them and what do you want from them?
Q2-17	When do you need to contact them?

Q2-18	How do you need to contact them?
Q2-19	What is a work handover procedure? Do you know any work handover procedure about your position? If yes, could you please describe it?
Q2-20	What are SO 9001:2008 requirements?

Step 6 is to answer the questions in step 5. In order to answer Q2-1 to Q2-18 questions listed in Table 24, face to face interviews were conducted with each ADP's member and 7 external stakeholders from other sections. Stakeholders from ADP (i.e., ADP's members) are defined in the organizational chart in Fig. 42. The stakeholders in the chart were renamed to members and respective number to replace the real names of the employees. Interviews of external stakeholders included 1) drainage design & construction, 2) environmental planning, 3) strategic planning of drainage planning, 4) environmental monitoring of drainage services, 5) private development, 6) sustainable development of the office of biodiversity, and 7) environmental services of drainage operations. Besides the interviews, related documents in Table 25 were also reviewed in order to gain a better understanding of Drainage Services, Drainage Planning Section and ADP activities. These two main sources of information guided to answers Q2-1 to Q2-18 questions. The first part of Q 2-19 was answered by searching on the Internet. The second part was responded by interviewing ADP's members. Q2-20 was answered by reviewing the ISO standard 9001:2008 (ISO, 2008a).

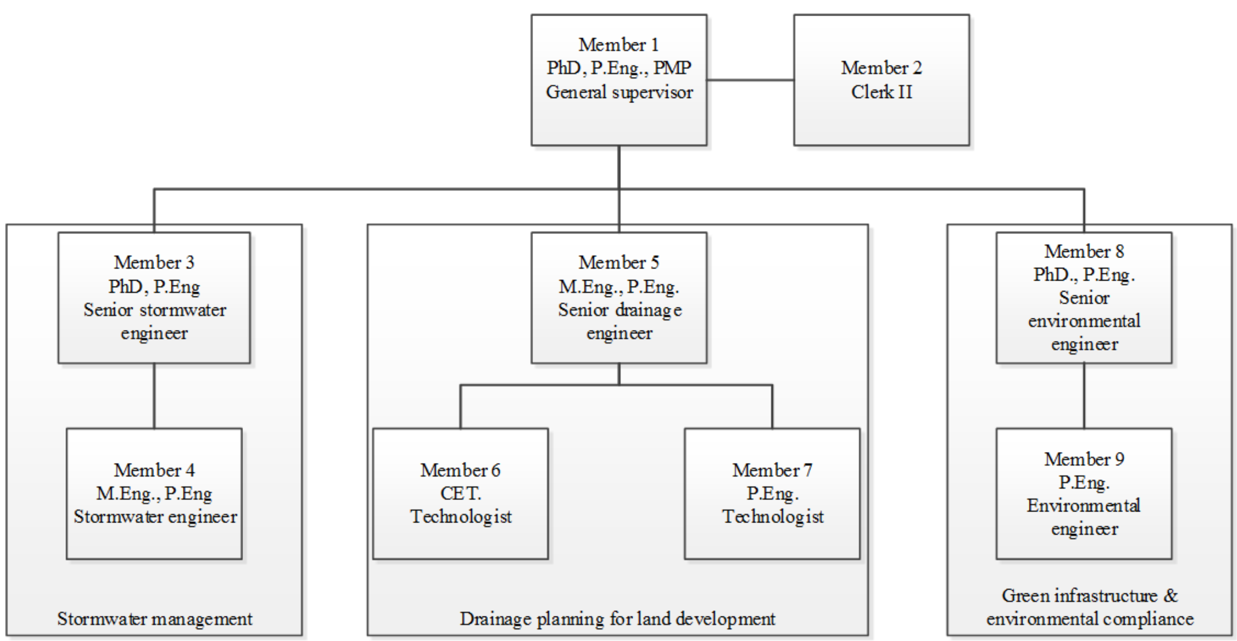

Fig. 42 ADP's organizational chart (April 2013)

Table 25 List of related documents

#	List of related documents
1	City Council-approved 2004-2014 Drainage Master Plan, ISO 14001 and the 10-year Approval-to-Operate (2005-2015) (The City of Edmonton, 2012d)
2	Design and Construction Standards, Volume 3: Drainage (The City of Edmonton, 2012c).
3	Drainage Services Stormwater Quality Strategy (The City of Edmonton, 2006).
4	Erosion and Sedimentation Control Guideline (The City of Edmonton, 2005b).
5	Erosion and Sedimentation Control Field Manual (The City of Edmonton, 2005a).
6	Low Impact Development Best Management Practices Design Guide Edition 1.0 (The City of Edmonton, 2011a).
7	The City of Edmonton Drainage Services Master Plan 2004-2014 Implementation and Strategies (The City of Edmonton, 2004).
8	The Way We Grow, Municipal Development Plan (MDP), Bylaw 15100 (The City of Edmonton, 2010c); especially section 7.0.
9	The Way We Green, The City of Edmonton's Environmental Strategic Plan (The City of Edmonton, 2011b).
10	The City of Edmonton, Bylaw 16200, Drainage Bylaw (The City of Edmonton, 2013a).
11	City of Edmonton Wetland Strategy (The City of Edmonton, 2012b).
12	Environmental Management System (Drainage Services Branch & Asset Management and Public Works Department, 2010).
13	Terms of reference for the preparation and amendment of residential area structure plans (ASP) (The City of Edmonton, 2010a).
14	Terms of reference for the preparation and amendment of residential neighbourhood structure plans (NSP) (The City of Edmonton, 2010b).
15	City of Edmonton Total Loading Plan (TLP) (The City of Edmonton, 2009).
16	City of Edmonton Stormwater Quality Control Strategy & Action Plan (The City of Edmonton, 2008).

Step 6 answers several questions. Q2-1 to Q2-18 were recorded in notes and rewritten in tables. Q2-1 to Q2-18 were classified and assigned to questionnaires. Two kinds of questionnaires were created to guide the interviews. The first kind of questionnaires including 12 questions, illustrated in Fig. 43, was used with ADP's members. The second kind of questionnaire including 7 questions, illustrated in Fig. 44, was used with external stakeholders. The questionnaires and answers were used to create workflow diagrams. Workflows and instances of SIPOC diagrams. Workflow diagrams were created for the whole ADP (see to Fig. 45), for each group (see Fig. 47, Fig. 50, and Fig. 54), and for each member (see Fig. 46, Fig. 48, Fig. 49, Fig. 51, Fig. 52, Fig. 53, Fig. 55 and Fig. 56). Fig. 45 defines ADP's general workflow. Fig. 45 is an overview of the technical processes executed by three groups (i.e., drainage planning for land development, stormwater management, and green infrastructure & environment compliance) and their respective interactions. The figure starts with the originator of all ADP projects (drainage planning), inputs (i.e., new private, residential or commercial project; special projects; old projects updates or upgrades; new requirements; and inquiries), and conditions to start the work of ADP. The main body of the figure indicates ADP processes, interactions with external stakeholders, work in process, deliverables, and their receivers. The general supervisor workflow in Fig. 46 supports managerially the technical processes in Fig. 45. Fig. 47 expands the technical processes in Fig. 45 executed by the green infrastructure & environmental compliance group. Fig. 48 and Fig. 49 expands the technical processes in Fig. 47 executed by each of the two members of the green infrastructure & environmental compliance group. Fig. 50 expands the technical process in Fig. 45 executed by the drainage planning for land development group. Fig. 51, Fig. 52 and Fig. 53 expands the technical process in Fig. 50 executed by each of three members of the drainage planning for land development group. Fig. 54 expands the technical process in Fig. 45 executed by the stormwater management group. Fig. 55 and Fig. 56 expands the technical process in Fig. 54 executed by each of the two members of the stormwater management group. In synthesis, Fig. 47 to Fig. 56 expands the technical processes in Fig. 45, while Fig. 46 provides managerial support to the previous figures. The figures define the context of operations of ADP including life cycle perspective: it all starts with projects or project requests from drainage planning and ends with strategies and plans for stakeholders (e.g., land developers, drainage services, Alberta regulators, third party auditors, financial management, roadway constructors, transportation services, utilities companies, Edmonton residents, public services, etc. The operations in the figures define the needed and accountable human resource[37] from ADP. The workflow diagrams were reviewed and approved by these stakeholders.

[37] Resources are consumed or used during a process. Human resources (aka people) (e.g., competence and capabilities) are one kind of resource. Other kinds of resources are 1) infrastructure (e.g., buildings and associated utilities, equipment including hardware and software, transportation resources, and ICT), 2) financial, 3) the environment for the operation of processes (aka work environment) (e.g., human factors including social and psychological, physical

A.1. Green Infrastructure & Environmental Compliance group interviews

XXX - Project Interview - Developing a Total Quality Management System for ADP

Interviewer	Time	Date
XXX XXX	10:45- 11:45	July 24, 2013
Interviewee	**Position**	**Group**
XXX XXX	Senior environmental engineer	Green infrastructure & Environmental Compliance

#	Questions
Q2-1	**What are the tasks and responsibilities of your group?** 1. Environmental review; 2. LID implementation; 3. Collaborating with other branches in stormwater projects.
Q2-2	**Who does the group interact with (other groups, sub-sections or external stakeholders)?** ➤ Other groups and sub-sections in Drainage service ➤ Environmental planning ➤ Development service ➤ Parks, transportation department
Q2-3	**What, when, and how this interaction happen (input and output)?** WHEN ➤ Developing strategies at the planning level. If other groups have projects, we need to be involved at beginning. ➤ Identifying the stakeholders for other department's projects. ➤ Contacting with other groups to see the performance of LID.
Q2-4	**What kinds of positions are included in your group?** One senior environmental engineer and one environmental engineer.

Q2-5	**What are your mainly tasks and responsibilities?** 1. Leading LID implementation (demonstration, training, research) 2. Supervising environmental review 3. Identifying the initiate of stormwater projects
Q2-6	**Who send these tasks to you? (task 1, task 2, etc.)** Task 1 and task 3 are from general supervisor. Task 2 is from current planning branch.
Q2-7	**When (under such situation) and how do you receive these tasks?** Having new LID implementation and environmental review requests.
Q2-8	**How do you fulfil these tasks? What knowledge, skill, and technology do you need for each task?** Technical knowledge, communication skills, and project management knowledge.
Q2-9	**Who do you need to interact with when you fulfill your tasks? When and how?** ➤ General supervisor (approve my document) ➤ Junior Environmental Engineer (assign tasks to him) ➤ And other branches.
Q2-10	**What are the expected deliverables for each task?** 1. LID implementation strategy 2. Comments for the report
Q2-11	**Who do you need to send these deliverables to? How?** ➤ General supervisor ➤ Shared with our stakeholders (if the reports impact on other branches).
Q2-12	**Do you know any work handover procedure about your position? If yes, could you please describe it?** No. The supervisor will introduce the work environment and projects.

Fig. 43 Sample questionnaires and answers recorded for the senior environmental engineer position in green infrastructure & environmental compliance

factors including temperature, heat, humidity, light, airflow, hygiene, and noise), 4) monitoring & measuring (e.g., measurement traceability, measuring equipment, and calibration), and 5) organizational knowledge (e.g., IP, technologies, standards, and experience) (ISO, 2015b).

A.1. **Private Development interview**

XXX - Project Interview - Developing a Total Quality Management System for ADP

Interviewer	**Time**	**Date**
XXX XXX	10:00 am – 10:45 am	August 21, 2013
Interviewee	**Position**	**Group**
XXX XXX	General Supervisor	Private Development

#	Questions
Q1	**Could you introduce your group briefly? (responsibilities and tasks)** We deal with ➢ Land development done by developers ➢ Neighborhood Area Structure Plan and down level ➢ Reviewing and reporting neighborhood design parts to determine if the system can be implemented ➢ Rezoning existing mature neighborhood and intend developments to see if this neighborhood works ➢ Inspection new construction, ➢ Review drainage applications that should match the AMP ➢ More detailed stuff, focusing on detailed engineering design and developing coordination to build the infrastructure
Q2	**What is the working relation between your group and ADP group?** ➢ We work on the neighborhood level and need to make sure all our projects matching the AMP; ➢ Rezoning application. When there are changes about the existing system, we need to collaborate with ADP, to see if the old system can handle the change development; ➢ We receive complaints from land owners. When they come to us, if it is related to the older neighborhood, SEB's group will be involved; ➢ For the development proposes, we identify further development and deal with the technology part. ADP commits to get consultant for us. They establish the guideline; ➢ When we are involved in projects that we are not familiar with, we may get help from ADP. For example, Gerry gets involved in transportation projects, he is familiar with it. He can be involved in the project related to transportation that we are not familiar with.
Q3	**Who are the main contacts in ADP? Why are they?** MK and Gerry: The AMP and area development proposals have impacts on the whole system, so we have to involve with them. XL: The LID applications affect the natural area, so we need to address LID applications into our neighborhood development. Sometimes, her group looks for information from us. Stephen: We receive complains about the existing neighborhood, so we refer the issues to them. For the new area development, we need to consider about the flood prevention and erosion control.
Q4	**What do you receive from ADP and what do they want from you?** ADP shares the AMP and ASP with us.
Q5	**What do you send to them and what do you want from them? (If possible, create correspondence among answer Q3, Q4, and Q5)** ➢ When AMP updates, it may cause big issues about the existing neighborhood. Once we update the existing area development plan, we need to get approval from ADP; ➢ We send our applications and ASP proposal to ADP, to wait for their review and comments; ➢ We receive complains about drainage system, so we send these complains to ADP.
Q6	**When do you need to contact them?** ➢ Everything involved in AMP ➢ Issues with existing neighborhood development ➢ Looking for more information about old existing systems
Q7	**How do you need to contact them?** Email, face to face talk, phone call, meeting

Fig. 44 Sample questionnaires and answers recorded for the general supervisor position in private development

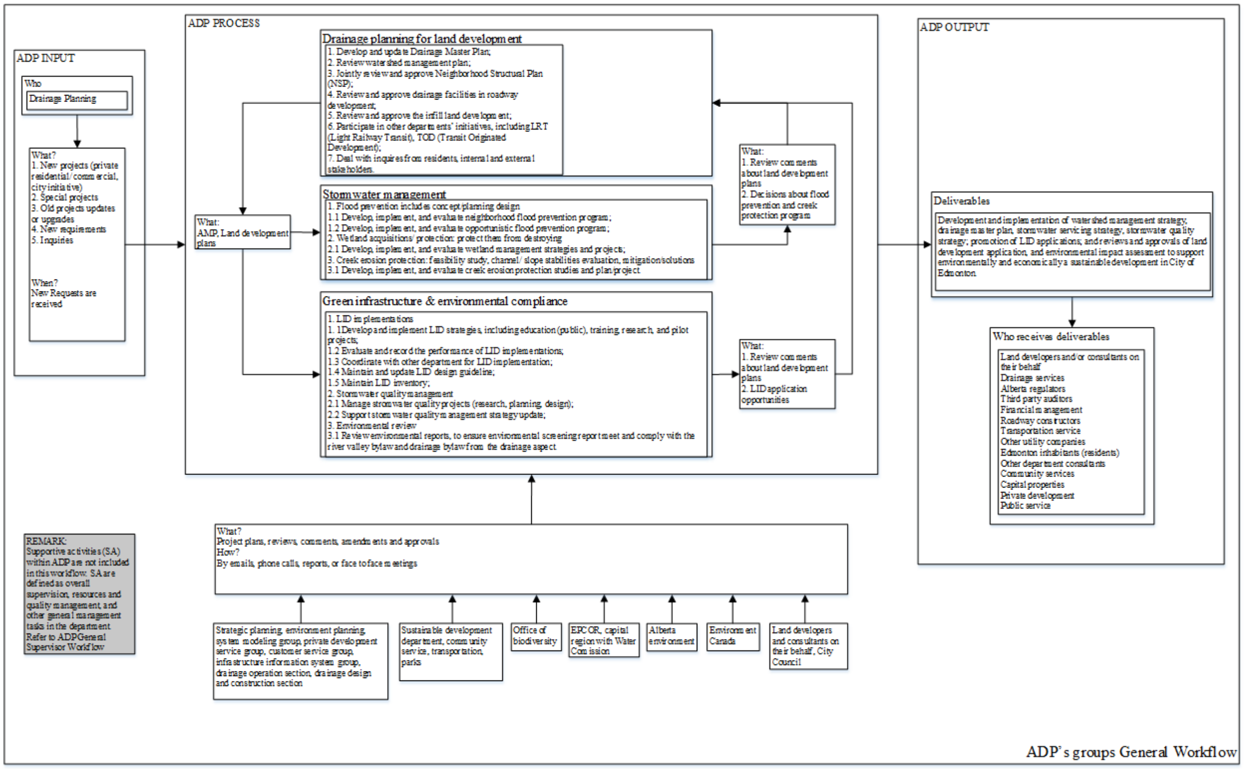

Fig. 45 ADP's general workflow

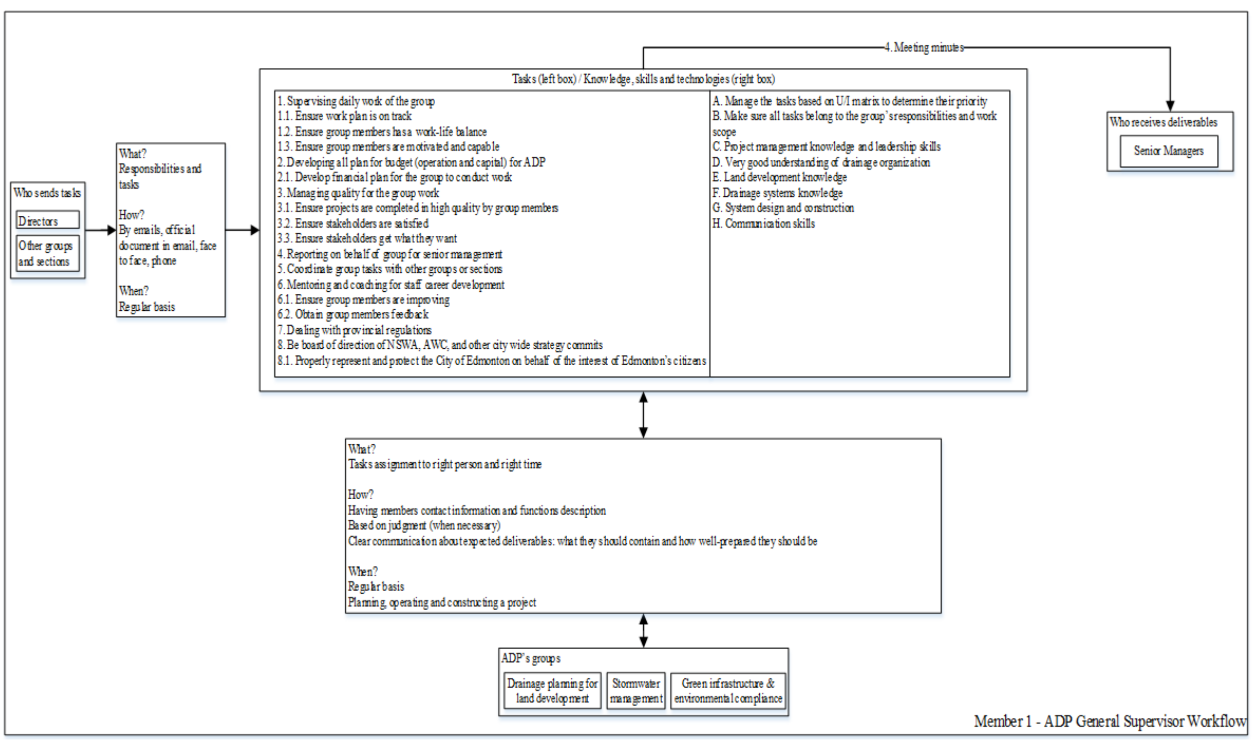

Fig. 46 ADP's general supervisor workflow

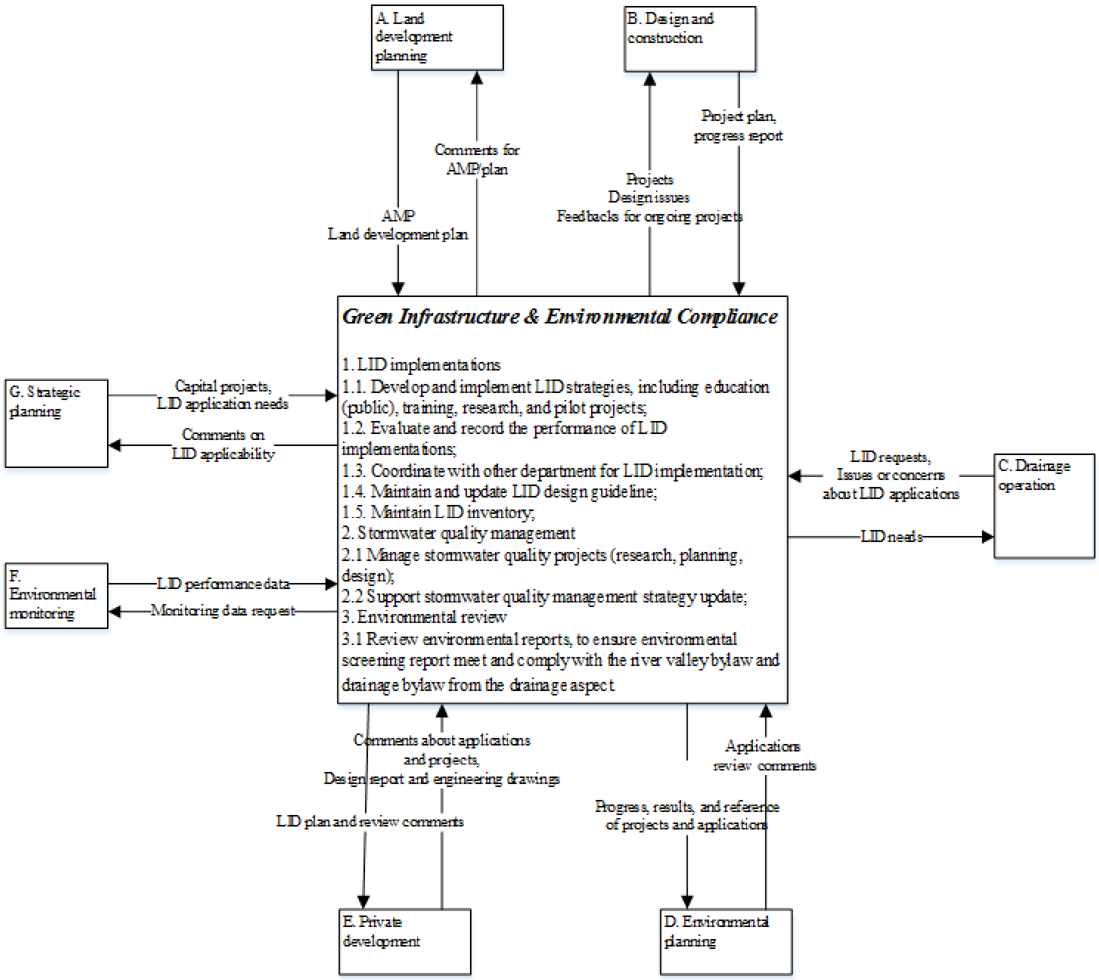

Fig. 47 Green infrastructure & environmental compliance group workflow

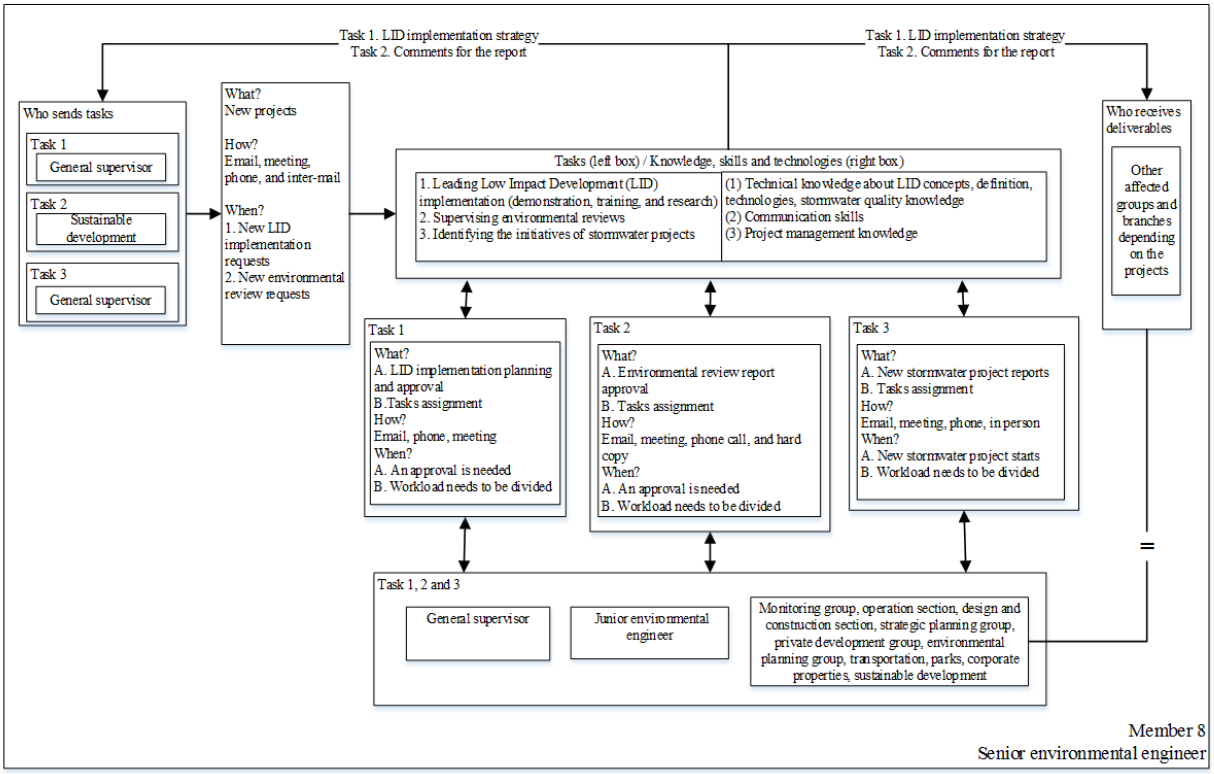

Fig. 48 Senior environmental engineer

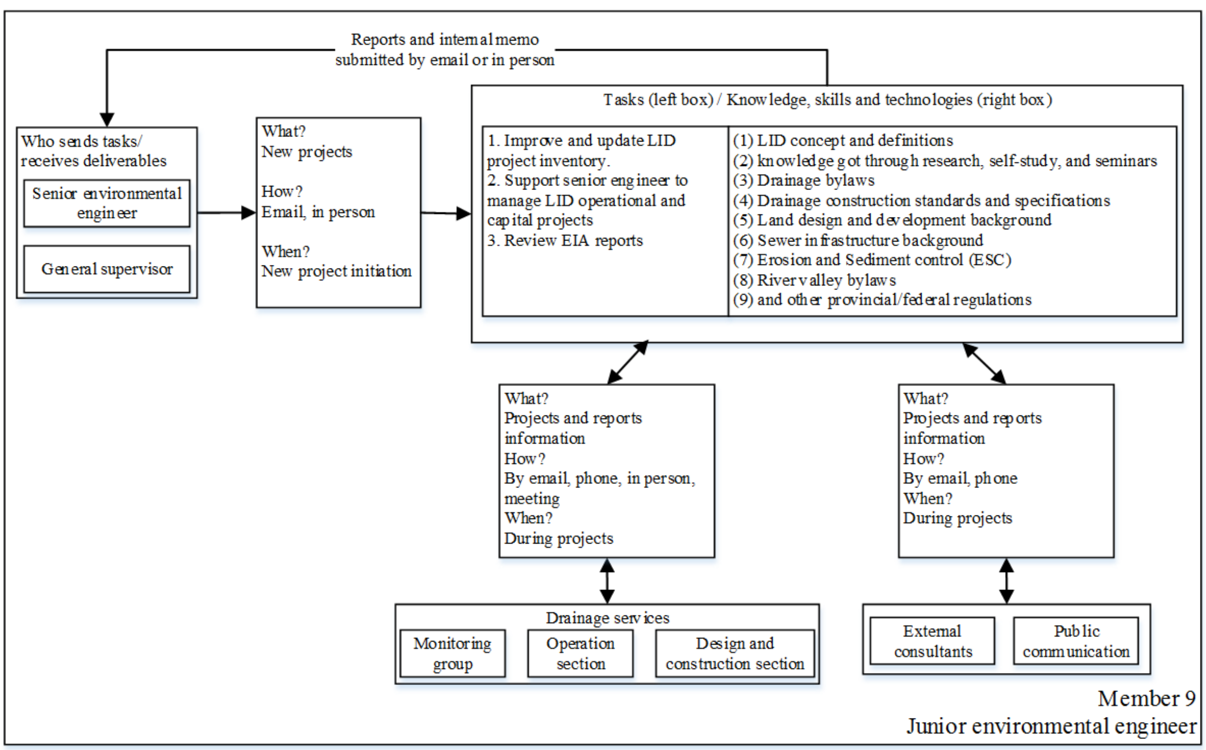

Fig. 49 Junior environmental engineer

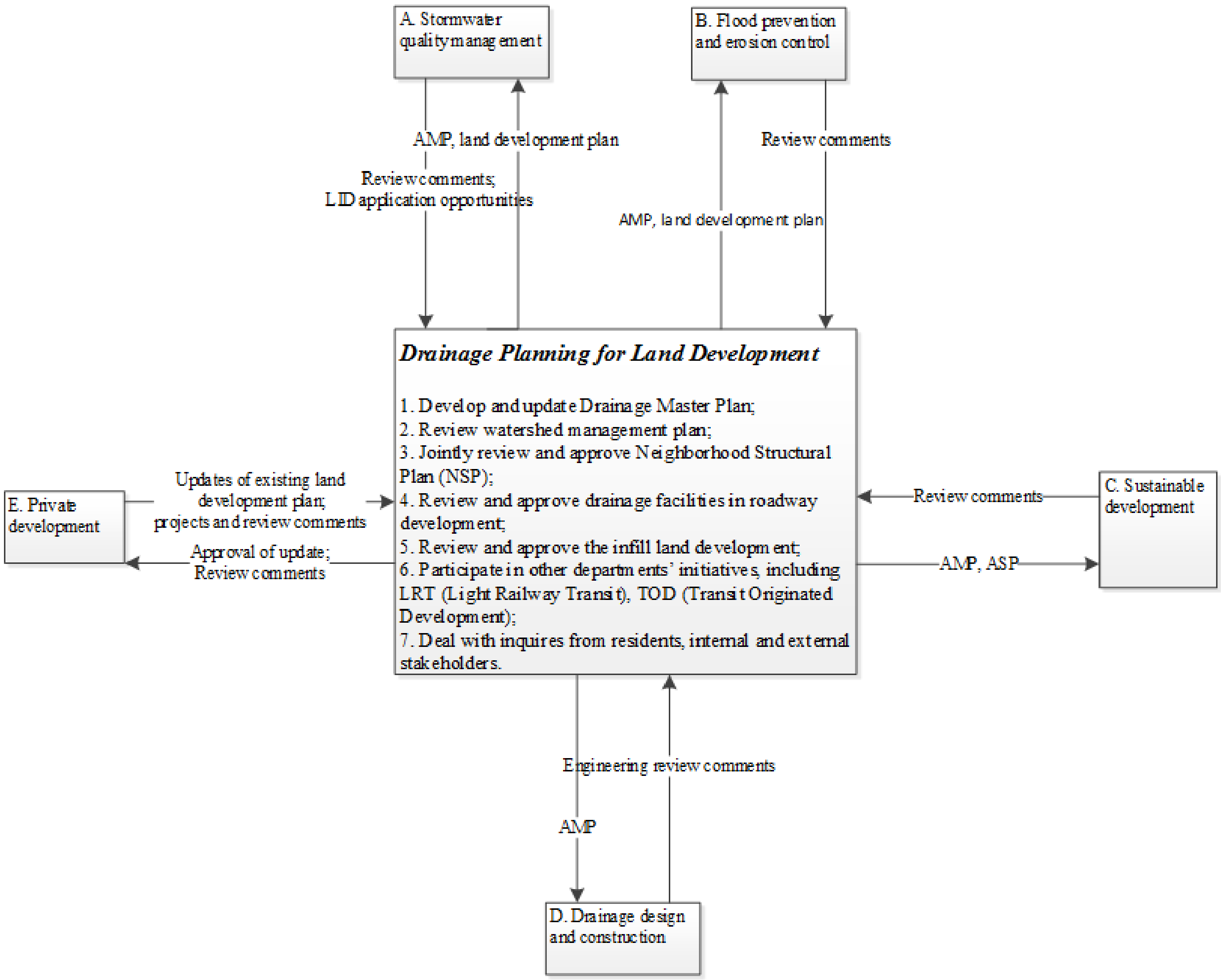

Fig. 50 Drainage planning for land development group workflow

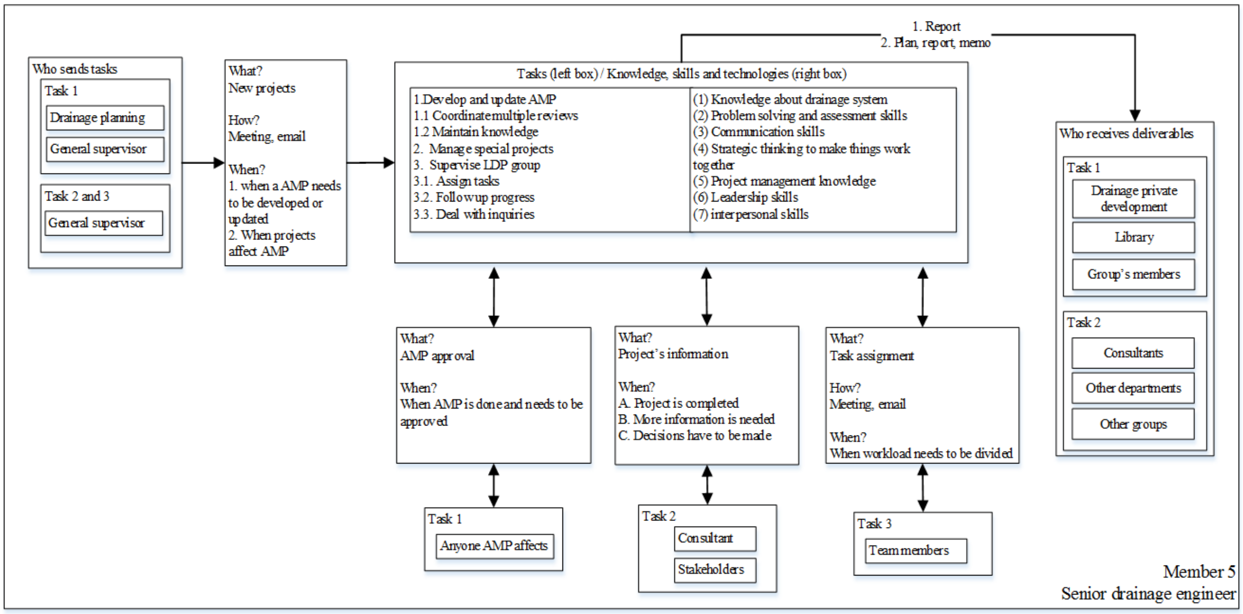

Fig. 51 Senior drainage engineer

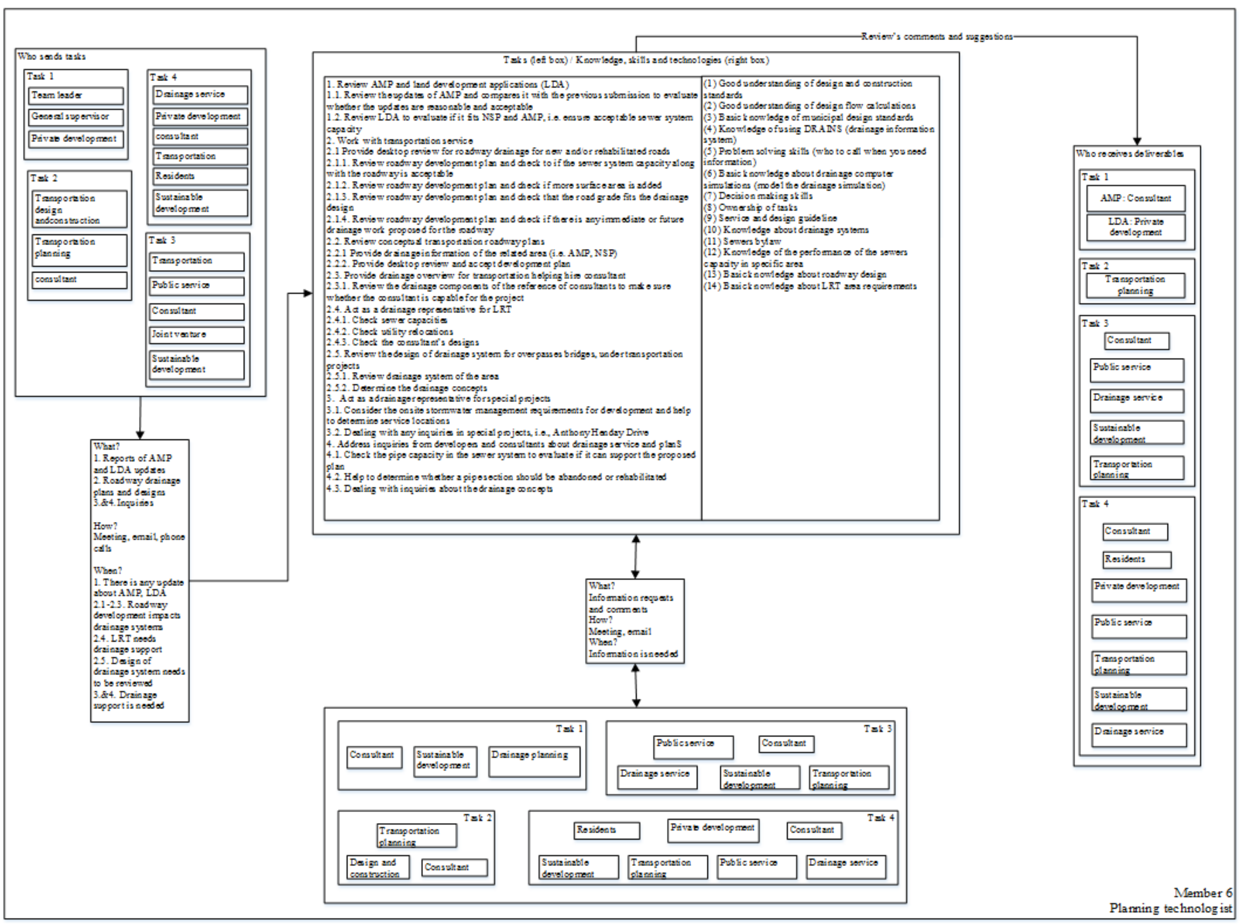

Fig. 52 Planning technologist

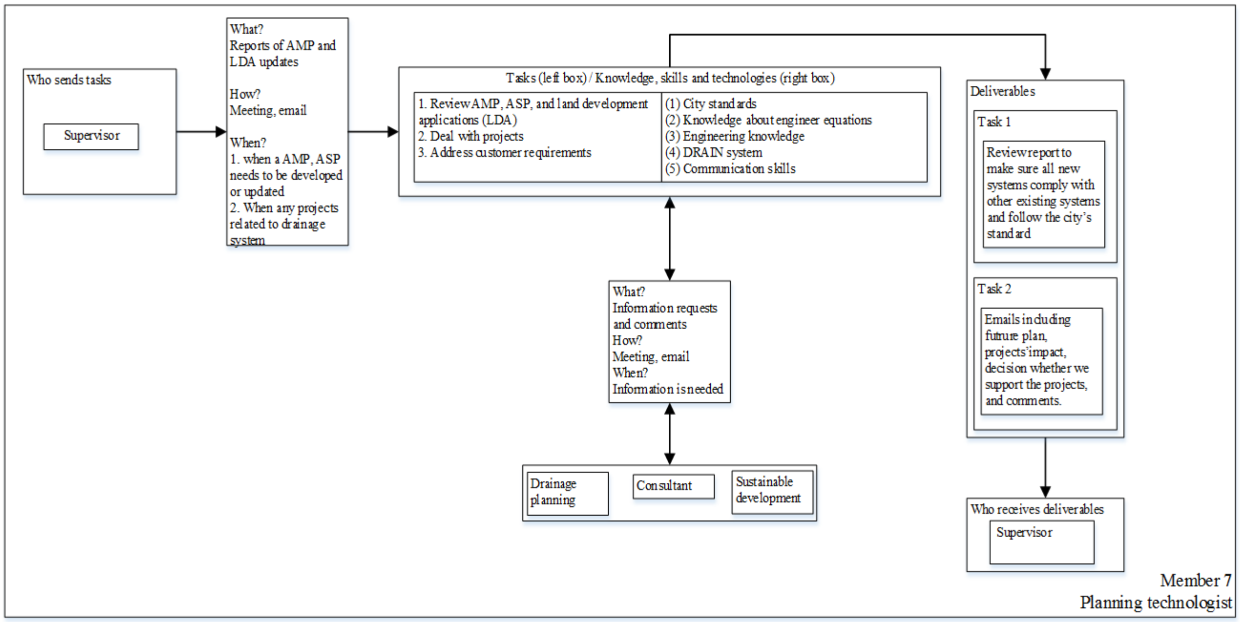

Fig. 53 Planning technologist

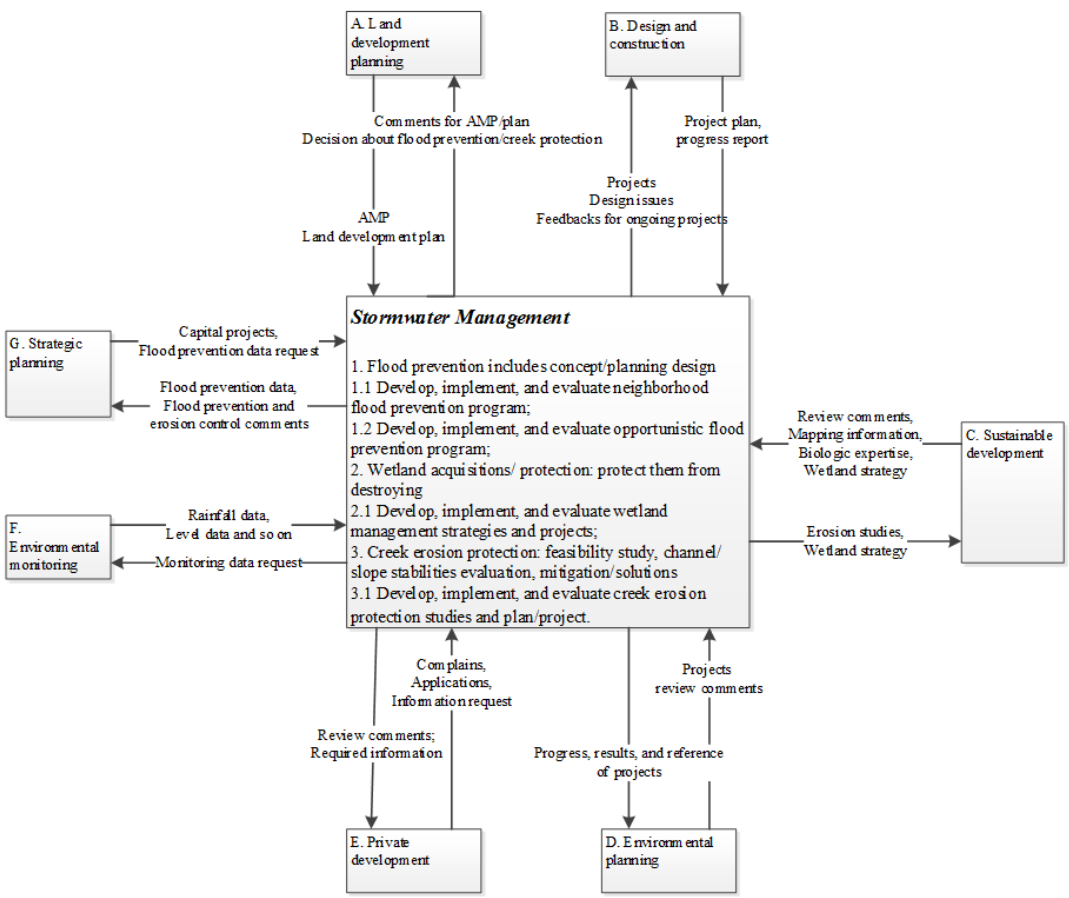

Fig. 54 Stormwater management group workflow

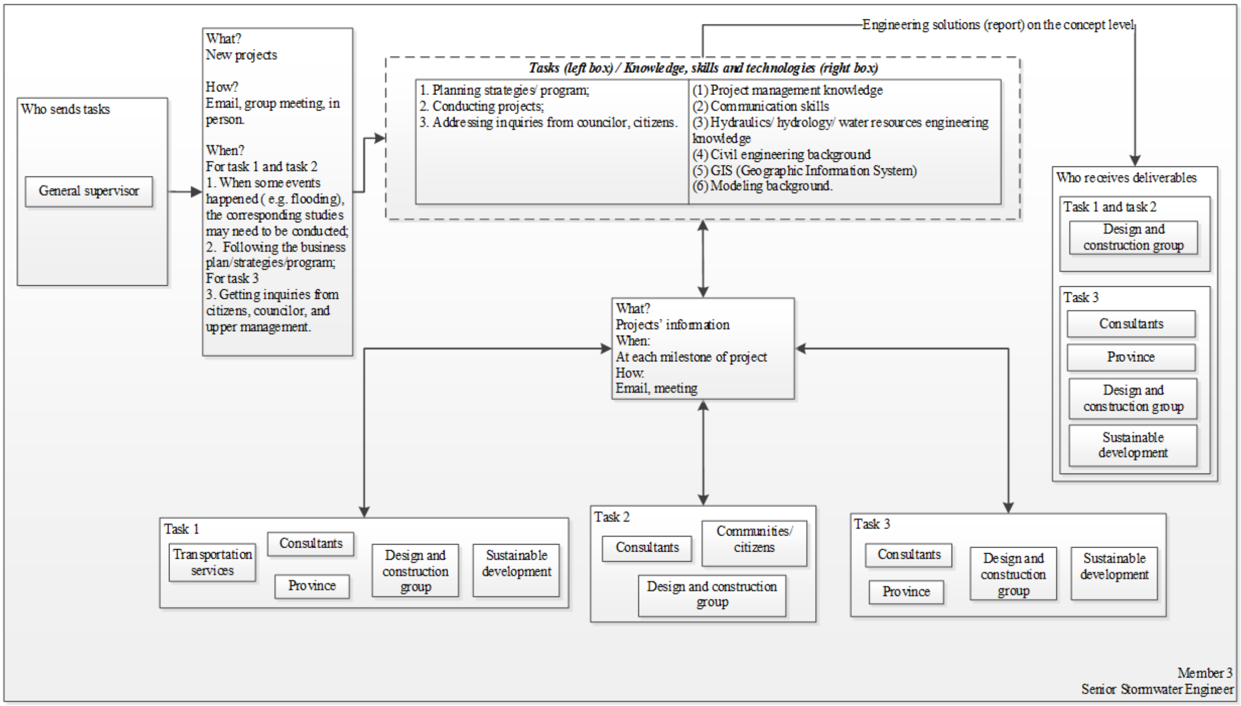

Fig. 55 Senior stormwater engineer

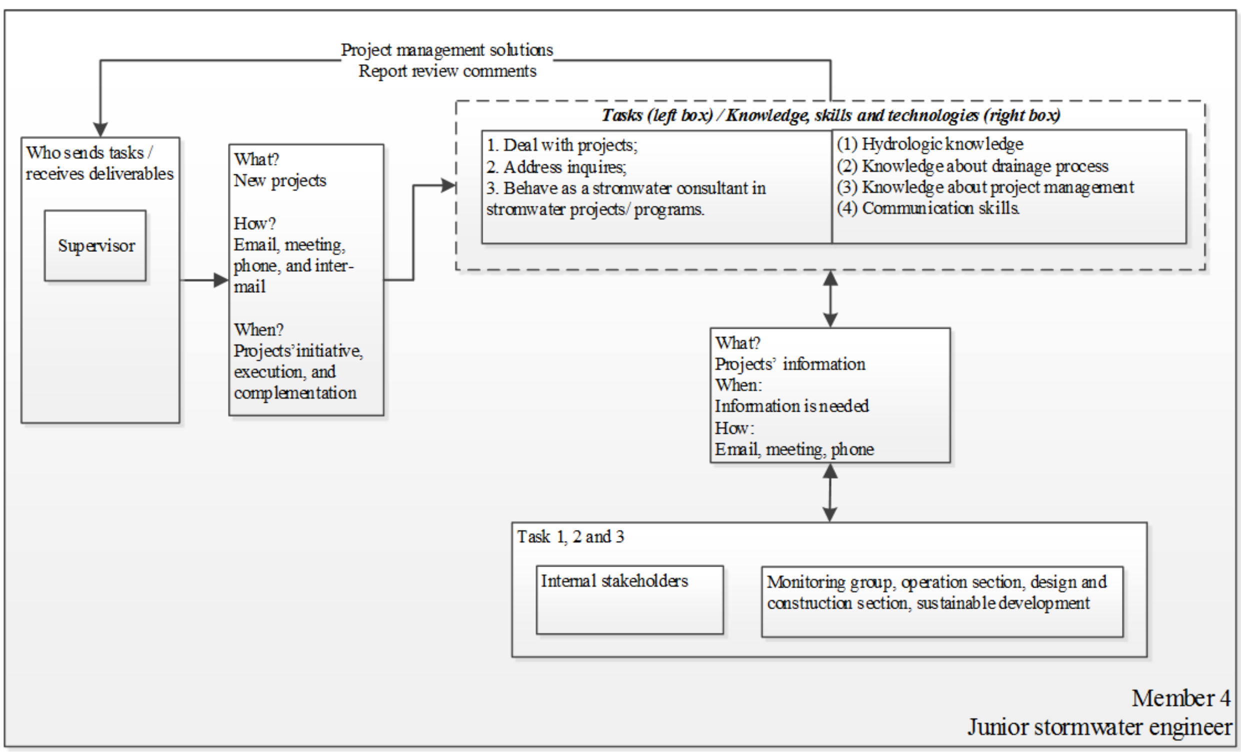

Fig. 56 Junior stormwater environmental engineer

Step 6 also answers the question Q2-19 in Table 24. Q2-19 is about a work handover procedure. Work in general refers to projects and activities related to its life cycle (i.e., from its inception to its closure) (Project Management Institute, 2013, pp. 38-47). Handover is to transfer knowledge about the work from one leaving person to one coming person. A procedure is an information item presenting an ordered series of steps to perform a process, activity, or task. Thus, a work handover procedure is an information item presenting an ordered series of steps to transfer knowledge about projects and activities related to its life cycle from one leaving person to one coming person. From the interviews, it was found that there was no formal/standard handover procedure in place. As a result, a generic handover procedure with two steps was suggested: 1) collecting needed knowledge from the leaving member, and 2) transferring the collected knowledge to the coming person. Collecting needed knowledge (i.e. step 1) was divided into the three components in Fig. 57: 1) knowledge about job tasks and responsibilities, 2) knowledge about ongoing projects, and 3) knowledge about previous projects. Details about job tasks and responsibilities are related to the corresponding workflows from Fig. 45 to Fig. 56, where specific responsibilities or work instructions shall be specified. The workflows are generic knowledge of the operations of ADP to manage projects. Knowledge about ongoing projects shall follow the 10 knowledge areas (i.e., project integration management, project scope management, project time management, project cost management, project quality management, project human resource management, project communication management, project risk management, project procurement management, and project stakeholder management), processes, and outputs defined by the Project Management Institute (2013). Two generic templates were defined as shown in Table 26 and Table 27. Complementing details or other required knowledge about ongoing projects shall follow the 10 knowledge areas, processes, and outputs by the Project Management Institute (2013). Some ADP projects are about upgrading/updating previous ones (such as AMP[38], ASP or NSP updating and amendment). Therefore, it is important to guarantee access to previous project knowledge (i.e., documents). The records of previous projects shall be maintained. Table 28 shows generic information to transfer about ongoing project to incoming members. Documentation about previous projects shall define the 10 knowledge areas, processes, and outputs by the Project Management Institute (2013).

[38] AMP stands for Area Master Plan, ASP for Area Structure Plan, and NSP for Neighborhood Structure Plan.

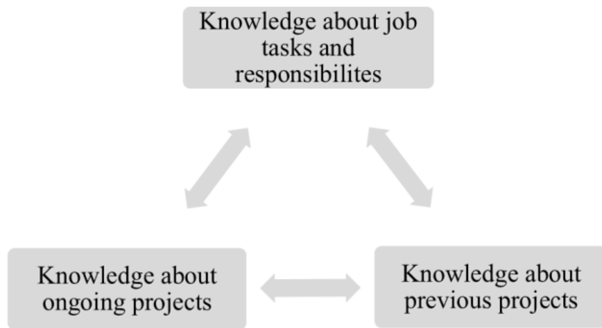

Fig. 57 Three kind of knowledge to be transferred

Table 26 Project ID and sponsor related contact information

Project ID	Sponsor	Organization	Job position	Telephone number	Email	Notes

Table 27 Project ID, other details, and project team

Project ID	Activities already done	Activities in process	Expected due date	Related documents	Critical issues /changes/priorities	Project team

Table 28 Previous projects **information to be transferred**

Project ID	Stakeholders involved	Completion date	Where to find related documentation	How to access to related documentation

Step 6 concludes answering the question Q2-20. This question intends to define the ISO 9001:2008 requirements. The requirements are defined in the international standard (ISO, 2008a). The model of a process-based quality management system shown in Fig. 58. The model illustrates high level process linkages proposed in ISO 9001:2008. In general, the model covers all the requirements in ISO 9001:2008, but it does not show processes at a detailed level. ISO 9001:2008 specifies requirements for a QMS (i.e., quality management system) where an organization: 1) needs to demonstrate its ability to consistently provide product that meets customer and applicable statutory and regulatory requirements, and 2) aims to enhance customer satisfaction through the effective application of the system, including processes for continual improvement of the system and the assurance of conformity to customer and applicable statutory and regulatory requirements. Considering the model in Fig. 58, the scope of the QMS covers all the transformation processes from customer requirements to customer satisfaction. During the transformation, ISO 9001:2008 prescribes requirements for 1) the QMS, 2) management responsibility, 3) resource management, 4) product realization, 5 and measurement, analysis, and improvement. Requirements are broken down into categories and subcategories and summarized in Table 29. A further effort to initially understand the requirements in the context of the case study was done. Considering that the QMS is the overarching object between the requirements in the standard, the general requirements (a-f) for a QMS from ISO (2008b) where employed as a frame of reference to understand the requirements. The general requirements (a-f) for a QMS and their interaction with the other categories of requirements in Table 29 where understood as shown in Table 30. Table 30 lists the general requirements and aligned them recursively with the rest of categories of requirements. Documentation requirements from ISO (2008b) are listed in Table 31. Documentation requirements cover the whole scope of tasks in Table 30. The ISO 9001-2008 requirements in Table 30 is the TQMS guideline.

Step 7 is to update the product-environment system. Fig. 59 is the updated product-environment system in ROM representation. Considering scalability issues to update all the pervious information in a ROM representation, the structure of Fig. 41 was preserved. Fig. 59 differs from Fig. 41 in that the former include indexes to sections in the delivered report. This section contained further details about each of the indexed concepts in the ROM representation. That approach was used to deal with scalability issues. In the context of this thesis, the indexed in the figure has not meaning and are only for description purpose.

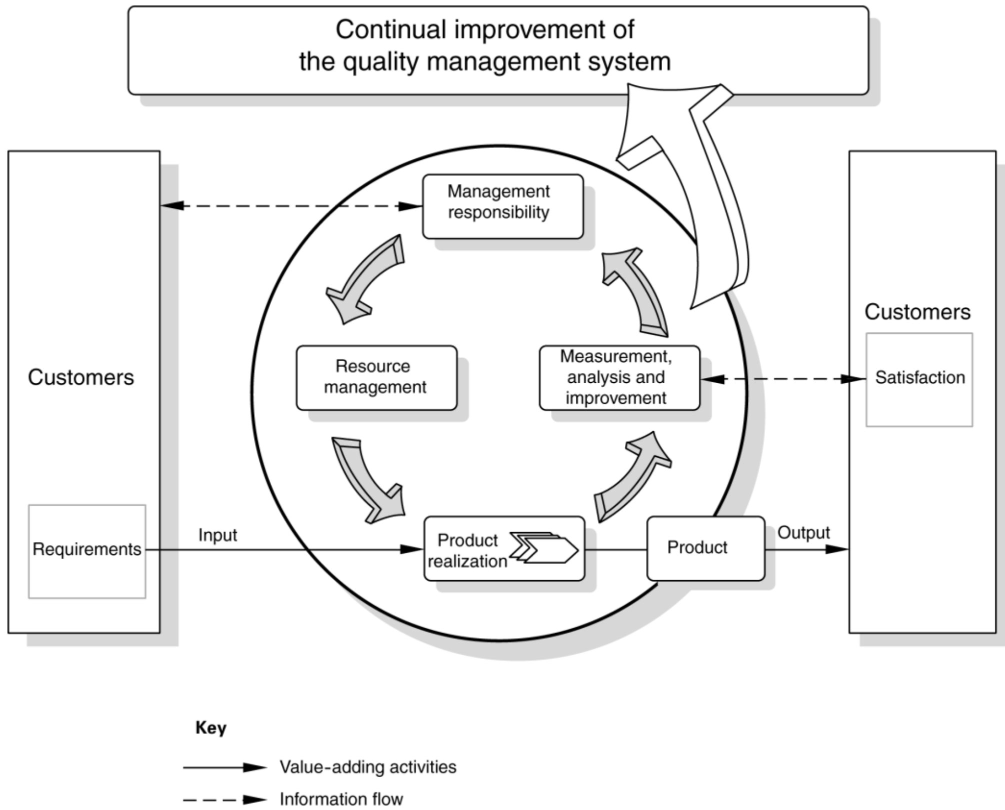

Fig. 58 Model of a process-based quality management system, adapted from ISO (2008b)

Table 29 Requirements: categories and subcategories from ISO (2008b)

Category	Subcategory
QMS	General requirement Documentation requirements
Management responsibility	Management commitment Customer focus Quality policy Planning Responsibility, authority, and communication Management review
Resources management	Provision of resources Human resources Infrastructure Work environment

Product realization	Planning of product realization Customer-related processes Design and development Purchasing Production and service provision Control of monitoring and measuring equipment
Measurement, analysis, and improvement	General Monitoring and measurement Control of nonconforming products Analysis of data Improvement

Table 30 ISO 9001:2008: general requirements for QMS

ISO 9001:2008 requirements	ISO 9001:2008 sub-requirements
1. Determine the processes needed for the QMS and their application throughout ADP	1. Management responsibility
	2. Resource management
	3. Service realization
	4. Measurement
	5. Analysis
	6. Improvement
2. Determine the sequence and interaction of the processes	1. Management responsibility
	2. Resource management
	3. Service realization
	4. Measurement
	5. Analysis
	6. Improvement
3. Determine criteria and methods needed to ensure that both the operation and control of the processes are effective	1. Management responsibility
	2. Resource management
	3. Service realization
	4. Measurement
	5. Analysis

	6. Improvement
4. Ensure the availability of resources and information necessary to support the operation and monitoring of these processes	1. Management responsibility
	2. Resource management
	3. Service realization
	4. Measurement
	5. Analysis
	6. Improvement
5. Monitor, measure where applicable, and analyze these processes	1. Management responsibility
	2. Resource management
	3. Service realization
	4. Measurement
	5. Analysis
	6. Improvement
6. Implement actions necessary to achieve planned results and continual improvement of these processes	1. Management responsibility
	2. Resource management
	3. Service realization
	4. Measurement
	5. Analysis
	6. Improvement

Table 31 ISO 9001:2008: documentation requirements for QMS (complements Table 29)

ISO 9001:2008 requirements	ISO 9001:2008 sub-requirements
7. General	1. Documented statements of a quality policy and quality objectives
	2. A quality manual
	3. Documented procedures and records required by ISO 9001:2008
	4. Documents, including records, determined by ADP to be necessary to ensure the effective planning, operation and control of the processes
8. Quality manual	1. Scope of the QMS
	2. Documented procedures established for the QMS, or references to them

	3. A description of the interaction between the processes of the QMS
9. Control of documents	1. To approve documents for adequacy prior to use
	2. To review and update as necessary and re-approve documents
	3. To ensure that changes and the current revision status of the documents are identified
	4. To ensure that relevant versions of applicable documents are available at point of use
	5. To ensure that documents remain legible and readily identifiable
	6. To ensure that documents of external origin determined by the organization to be necessary for the planning, operation of the QMS are identified and their distribution controlled
	7. To prevent the unintended use of obsolete documents, and to apply suitable identification to them if they are retained for any purpose
10. Control of records	1. A documented procedure to define the control needed for the identification, storage, protection, retrieval, retention and disposition of records

After completing the second iteration of questions and answers, environment analysis in EBD methodology has been completed. The result from this activity in the form of questions, answers, workflows, handover procedures, understanding of ISO 9001:2001 requirements, ROM representations are foundation to initiate conflict identification.

5.3.2 Conflict identification

Conflict identification is the second activity of EBD methodology, after the environment analysis. The goal of this section is to identify existing conflicts. Conflicts arise after conducting a systematic evaluation between the TQMS guideline (requirements in Table 30) to be designed and current ADP's environment components (i.e., workflows from Fig. 45 to Fig. 56). The results of conflict identification are the foundation of the third report - solution generation.

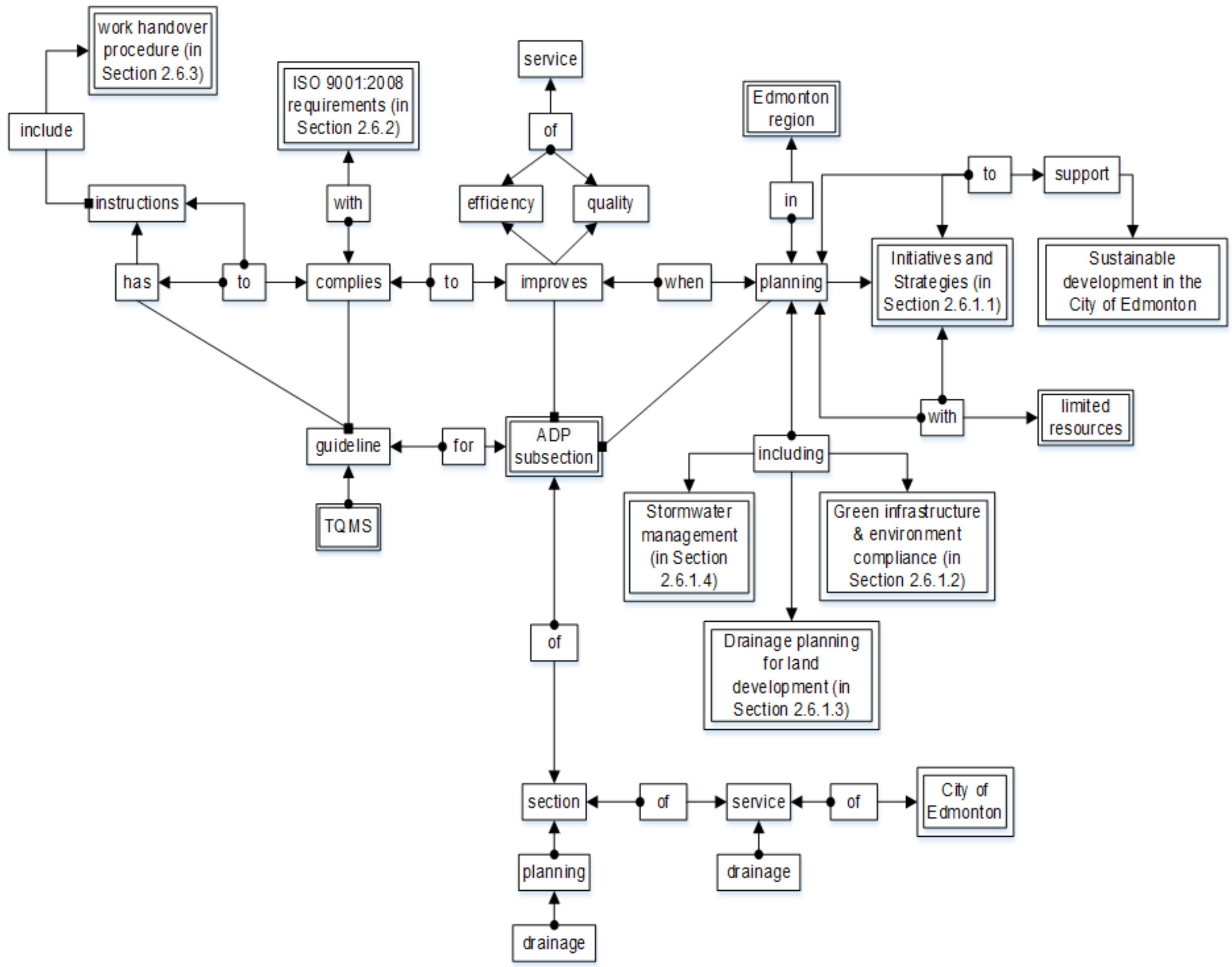

Fig. 59 ROM representation of the updated product-environment system

Conflict identification follows the process under research and development for EBD methodology by Zeng (2011, 2015). The process searches for conflict systematically in the environment system. The environment system is defined in Fig. 59. Conflicts arise while executing actions or between actions (i.e., verbs/predicates in Fig. 59) while executing them. Conflict identification is a systematic exhaustive search of gaps at the whole problem space (TQMS guideline) and actual status of ADP are implied in Fig. 59.

Table 32 shows the structure of a table that was used to conduct the systematic gap evaluations (i.e., conflict identification). The ISO 9001:2008 requirements are shown in the first two columns content on the left side in Table 32. The requirements regulate ADP's stakeholders, knowledge, skills and technologies, ADP's processes, and ADP's supporting documents. The third, fourth and fifth columns in the table represent how ADP's stakeholders, knowledge, skills and technologies, ADP's processes, and ADP's supporting documents comply to the ISO 9001:2008 requirements.

If there is no compliance to the ISO 9001:2008 requirements, the last column in the table will include a gap with the missing actions or resources. Details about the systematic gap evaluations can be in Appendix D (Section D.2)

Table 32 Gap evaluation: general structure

ISO 9001:2008 requirements[39]	ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders[40]	ADP's supporting documents	Gap evaluations
Requirement 1 to 10	Respective sub-requirements	ADP's processes complying with the requirement	ADP's stakeholders complying with the requirement	ADP's supporting documents complying with the requirement	Action or resource missing to comply with the requirements

During the systematic gaps evaluation, 40 gaps were found from Table 87 to Table 96 in Appendix D (Section D.2). The 40 gaps and their sources are summarized in Table 33. The 40 existing gaps can be divided into 4 categories:

- Unbalanced workload and weak motivation: due to the transformation of the Drainage Services branch, it was found that tasks distribution should be redefined to increase the efficiency of the service and motivation of ADP's group members. While solving this problem, it is possible that tasks balancing, training and supporting document updates are required.
- Indicators/metrics: Metrics known as key performance indicators (KPIs) shall be created to monitor ADP's processes, ADP's stakeholders (referring to ADP's group members and ADP's external stakeholders) and ADP's supporting documents. Other KPIs are needed to monitor the effectiveness and efficiency of the selected KPIs, management responsibilities and resources management.
- Process-method for measurement, analysis & improvement: a process-method shall be created to measure the KPIs, analyze them and improve continuously the performance of ADP subsection.

[39] ISO 9001:2008 requirements and sub-requirements in columns 1 and 2 in the table comes from Table 30 and Table 31. Hereafter, ISO 9001:2008 requirements are called ISOR for abbreviation purposes.
[40] ADP's stakeholders define the member, but from the corresponding workflows can be implied related knowledge, skills, and technologies.

- Documentation, record & integration: an integrated TQMS shall be created as well as all the required documentations and implied records.

Table 33 Conflict identification: identified gaps

Requirement	List of tables	Number of gaps
ISOR 1	Table 87	3
ISOR 2	Table 88	3
ISOR 3	Table 89	3
ISOR 4	Table 90	3
ISOR 5	Table 91	6
ISOR 6	Table 92	6
ISOR 7	Table 93	4
ISOR 8	Table 94	4
ISOR 9	Table 95	7
ISOR 10	Table 96	1
TOTAL		40 gaps

Solutions for the existing gaps will be generated in the solution generation activity of EBD methodology. The solutions will be part of the instructions that the TQMS guideline for ADP needs to comply with ISO 9001:2008 requirements.

5.3.3 Solution generation

Solution generation is the third activity of EBD methodology after the conflict identification. The goal of this activity is to provide a guideline with directions to close the 39 identified gaps in the conflict identification report. After closing the gaps, it is expected that ADP subsection will comply with ISO 9001:2008 requirements. Consequently, it is also expected that ADP will improve efficiency and quality of its service with the existing resources.

Solution generation follows the process suggested by Zeng (2011, 2015). Solution generation follows the following steps: 1) define ISO 9001:2008 requirements (short for ISORs) relationships, 2) use the relationships to guide the sequence solution generation, and 3) generate solutions for complying with ISORs.

Step 1 in solution generation is define the sequential relationships between the identified ISORs. Originally, ISORs were defined in Table 30 and Table 31. The sequential relationships are defined graphically in Fig. 60. The relationships were performed at the ISOR level. The relationships can also be defined at the sub-requirements level. Independent of the level, it is expected that both definitions of relationships shall agree.

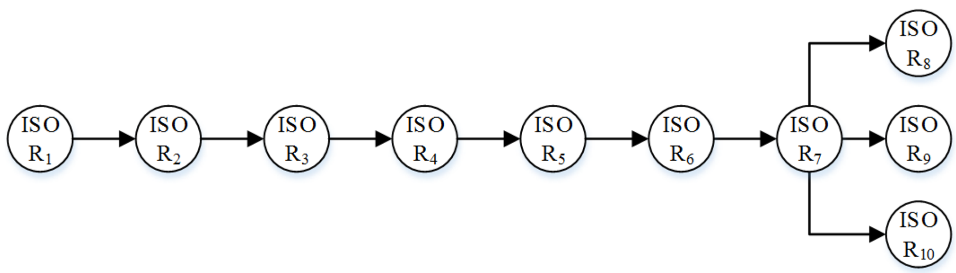

Fig. 60 Graphical relationships between ISO 9001:2008 requirements (ISORs)

Step 2 is to use the relationships in Fig. 60 to generate guide the sequence of solution generation. According to the figure, solutions shall proceed from left to right. The figure is transitive meaning that every solution moving towards the right side depends on all the preceding requirements and solutions. For example, solutions for $ISOR_7$ depends on solutions and requirements 1 to 6.

Step 3 is to generate solutions for complying with ISORs. Considering that there are several gaps, a procedure for solution generation was employed following Fig. 60. Fig. 61 defines the employed procedure which has a first step the input from Fig. 60. Considering that the expected outcome of the case study is a guideline, the procedure in Fig. 61 is used to close the gaps. Every identified gap can be closed by creating the needed solutions using suggestions by Hoyle (2009), Evans and Lindsay (2011), Evans and Lindsay (2005) or Heizer et al. (2014). The solutions from the procedure shall be used to fill out the proposed outline in Fig. 62.

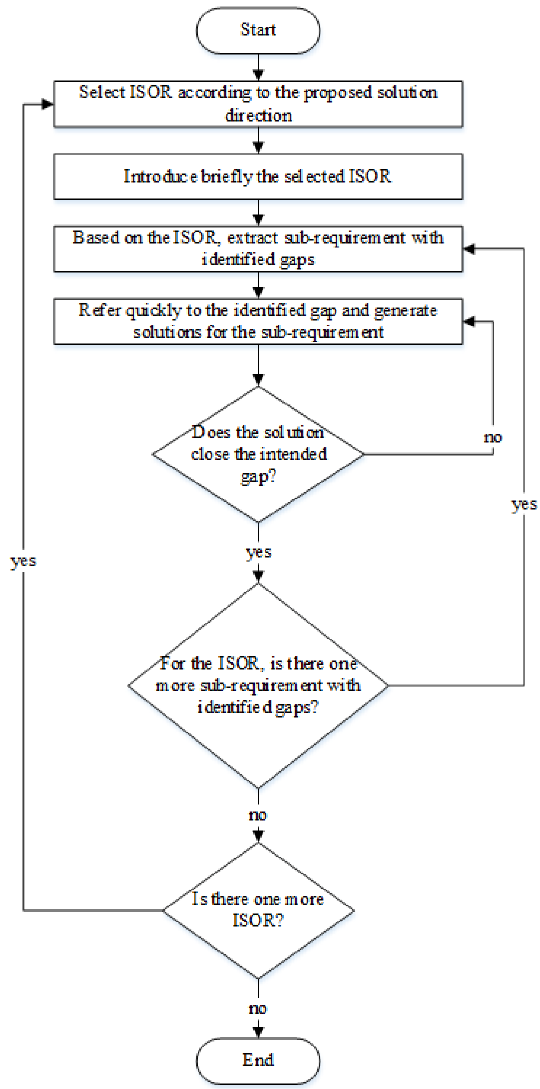

Fig. 61 Solution generation: procedure

At this stage of the case study, a high-level overview of the ADP's TQMS is illustrated in Fig. 63. The figure is called high-level because it only presents two workflows (i.e., Fig. 45 and Fig. 46). The two workflows were integrated as specified in the model in Fig. 58. The two workflows can increase the level of details by integrating the rest of workflows (i.e., Fig. 47 to Fig. 56). The relationships between all the workflows were defined in environment analysis, more specifically in iteration 2 (Section 5.3.1.2). Solution generation shall continue using Fig. 61 until all the identified gaps are closed, and the TQMS outline in Fig. 62 is completed. Possibly, at that time, an iteration of conflict identification activity shall be conducted as a review.

Appendix A. Total Quality Management System[1] proposed outline

1. Quality policy and objectives (to be created)
2. Scope of the TQMS (refer to environment analysis)
   a. *Exclusions (to be created)*
3. ADP organizational chart (refer to environment analysis)
4. ADP overall workflow (refer to environment analysis)
5. General Supervisor workflow (refer to environment analysis)
6. Members' workflows (refer to environment analysis)
7. Documents (to be partially created)
   a. *Management reviews document and internal audits (to be created)*
   b. *Document for nonconforming results analysis and improvement actions (to be created)*
   c. *Procedures for controlling documents (to be created)*
   d. *Procedures to define the control needed for records (to be created)*
   e. *Work handover procedure (refer environment analysis)*
8. Other existing ADP documents or reference to them (refer to environment analysis)
9. Records or reference to records (to be created)
10. Records templates (to be created)
    a. *Templates for recording external stakeholders' meetings and workload balance analysis (to be created)*
    b. *Template for recording communication of document updates (to be created)*
    c. *Meeting minutes template (to be created)*
    d. *Needed templates for creating each of the records in Table A.1 except to stated exclusion in the scope of the TQMS (to be created in section 2a).*
    e. *Other records template (to be created if needed)*

[1] This TQMS will include the quality manual

Table A.1 Records required by ISO 9001:2008, adapted from (ISO, 2008)

Clause	Record required
5.6.1	Management reviews
6.2.2 e)	Education, training, skills and experience
7.1 d)	Evidence that the realization processes and resulting product fulfil requirements
7.2.2	Results of the review of requirements related to the product and actions arising from the review
7.3.2	Design and development inputs relating to product requirements
7.3.4	Results of design and development reviews and any necessary actions
7.3.5	Results of design and development verification and any necessary actions
7.3.6	Results of design and development validation and any necessary actions
7.3.7	Results of the review of design and development changes and any necessary actions
7.4.1	Results of supplier evaluations and any necessary actions arising from the evaluations
7.5.2 d)	As required by the organization to demonstrate the validation of processes where the resulting output cannot be verified by subsequent monitoring or measurement
7.5.3	The unique identification of the product, where traceability is a requirement
7.5.4	Customer property that is lost, damaged or otherwise found to be unsuitable for use
7.6 a)	Basis used for calibration or verification of measuring equipment where no international or national measurement standards exist
7.6	Validity of the previous measuring results when the measuring equipment is found not to conform to requirements
7.6	Results of calibration and verification of measuring equipment
8.2.2	Internal audit results and follow-up actions
8.2.4	Indication of the person(s) authorizing release of product.
8.3	Nature of the product nonconformities and any subsequent actions taken, including concessions obtained
8.5.2 e)	Results of corrective action
8.5.3 d)	Results of preventive action

References

ISO. (2008). ISO 9000 Introduction and Support Package: Guidance on the Documentation Requirements of ISO 9001:2008: ISO.

Fig. 62 TQMS proposed outline

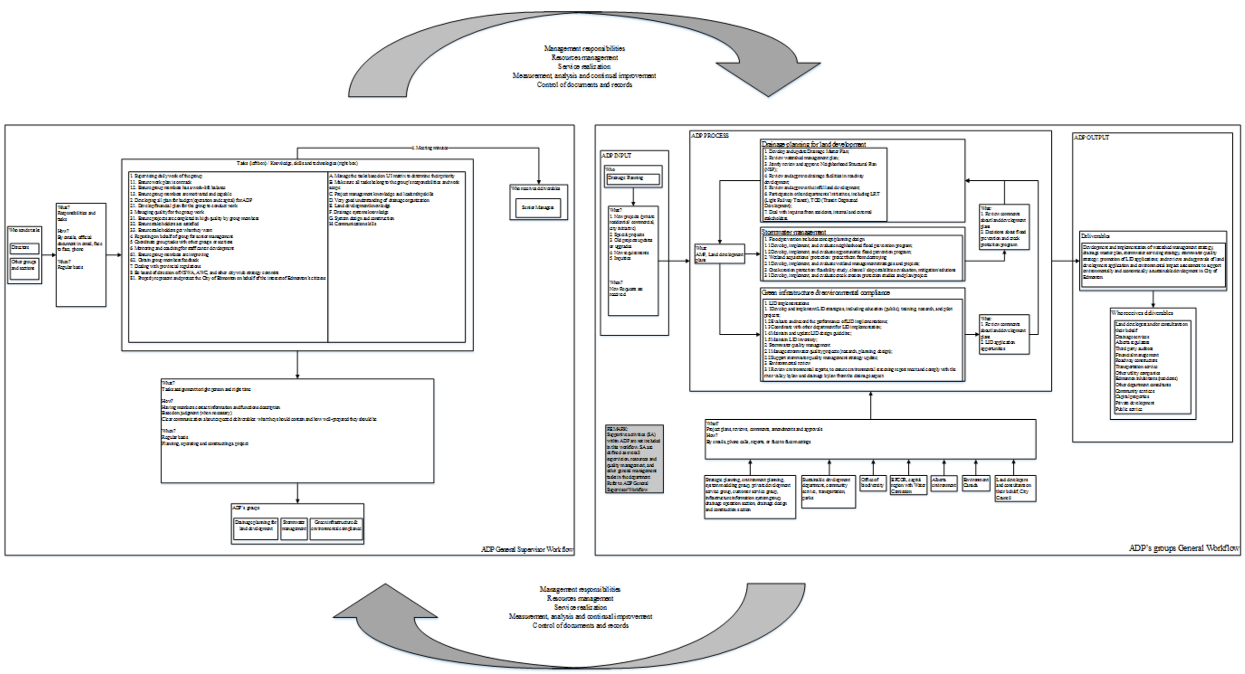

Fig. 63 A high level overview of ADP TQMS at this stage of design

5.4 Data analysis

Based on Chapter 3, retrospection employs EBD theory as the foundation for data analysis (Saldaña, 2009, pp. 8-13). In particular, the proposed core ontology complements EBD root concepts to form a coding scheme for data analysis. The coding scheme and its characterization is presented in Section 5.4.1. The characterization of the coding scheme is based on previous content in this chapter. Section 5.4.2 discusses the findings after evaluating the coding scheme in Section 5.4.1.

Table 34 EBD root concepts and the proposed core ontology (PCO) as coding scheme

EBD root concepts	Concepts in PCO
Natural environment	Environment[41], Interaction, Risk, Safety, State, Validation, Verification
Built environment	Architecture, Attribute, Availability, Baseline, Concept of operations, Concern, Document, Enabling system, Flexibility, Functional requirement, Interface, Issue, Need, Operational concept, Port, Product, Project, Quality, Reliability, Requirement, Resource, Service, Stakeholder requirement, Standard, System, System element, System requirement, System-of-interest, Trade-off
Human environment	Acquirer, Customer, Operator, Organization, Party, Stakeholder, Supplier, User
Design process	Activity, Process, Quality management
Life cycle	Life cycle, Life cycle model, Stage, System life cycle processes

5.4.1 Data analysis: the proposed core ontology as coding scheme

Data analysis uses EBD root concepts and the proposed core ontology as a coding scheme. The employed coding scheme is defined in Table 34. The data source to characterize the coding scheme is the content in this chapter. The coding scheme is characterized by finding instances (aka individuals) in the case study related to the concepts in Table 34. An instance can be a particular case of the concept, a synonym, or the concept itself. In the first two cases, the characterized

[41] Considering that concepts for the built and human environment are defined in the table, the term in this case is left for representing the natural environment. However, natural, built and human environment can conform the semantic meaning of the term in the proposed core ontology.

concepts can be included to the proposed core ontologies as instances, i.e., adding an "include" relation from the concept in the ontology to the characterized concept(s). In the second case, the concept in the proposed core ontology is just kept, but it is known to be valid.

The characterization of concepts is not exhaustive; i.e., at least one instance is allocated in the characterization to prove the validity of the concept. The characterization of concepts respect to the coding scheme is summarized in the remaining of this section (i.e., from Section 5.4.1.1 to Section 5.4.1.5).

5.4.1.1 Natural environment

The natural environment refers to all the [natural] laws in a product's working environment (Zeng, 2004a, 2015). Concepts in the proposed core ontology related to the natural environment are summarized in Table 35.

Table 35 Natural environment and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Natural environment	Environment	Land, stormwater, environmental & natural resources, erosion, sediments, flooding from extreme storm events, etc.
	Interaction	Interaction between groups (e.g., APD's staff and external stakeholders), grading and earthwork, etc.
	Risk	Project risk management, risk within [planning] process
	Safety	Public safety (flood prevention) and health (stormwater quality control or water pollution), etc.
	State	Current state of the organization, current state of the total quality management system
	Validation	Environmental permits, building permits and certificates of occupancy, etc.
	Verification	Drainage master plan review, environmental site assessment, historic and archaeologic assessment, market analysis and economic feasibility, engineering feasibility, etc.

5.4.1.2 Built environment

The built environments are the artefacts designed and created by human beings (e.g., man-made devices) (Zeng, 2004a, 2015). Concepts in the proposed core ontology related to the built environment are summarized in Table 36.

Table 36 Built environment and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Built environment	Architecture	Development patterns and principles
	Attribute	Stormwater quality[42], erosion [characterization of], nonconforming products [characterization of], high-quality project [characterization of], extreme storm events [characterization of], etc.
	Availability	Availability of resource, available at point of use, mandate in the 10 years approval to operate and The City of Edmonton Drainage Services Master Plan 2004 – 2014 Implementation and strategies requirements, etc.
	Baseline	Drainage master plan, ISO 14001, and 10-year Approval-to-Operate issued and regulated by the Province of Alberta.
	Concept of operations	Market analysis and economic feasibility, Engineering feasibility
	Concern	Provincial regulations, staff career development, city-wide strategy commits, etc.
	Document	Terms of reference for the preparation and amendment of residential area structure plans (ASP), Drainage Services Stormwater Quality Strategy, etc.
	Enabling system	Financial services and utilities, community services, transportation services, area & neighbourhood structure plans, etc.

[42] Stormwater quality may involve to analyze chemical, physical, biological, and radiological characteristics of water.

	Flexibility	Utilization of school surplus sites as space for stormwater management facilities for mature neighborhoods
	Functional requirement	Wastewater collection, Water distribution, Wastewater treatment, Water supply and treatment, Erosion and sediment control, proactive flood prevention, reactive flood prevention, improve stormwater quality, researching innovative technologies, developing innovative technologies, etc.
	Interface	Interfaces within [planning] process
	Issue	Critical issues, changes, priorities, issues and suggestions in GM (general manager) and external stakeholder's interviews
	Need	Need to comply with ISO 9001:2008 requirements, sociotechnical needs, need for documented information, needed resources, needed skills, knowledge, and technologies, etc.
	Operational concept	10-year Approval-to-Operate issued and regulated by the Province of Alberta, feasibility and site analysis, etc.
	Port	Meeting [flow of information], reports, feedback, deliverables, plans, strategies, reviews, etc.
	Product	Plans, strategies, low impact development guide, innovative technologies, etc.
	Project	Projects, city-wide flood prevention projects, special projects, project requests, etc.
	Quality	Quality, stormwater quality, etc.
	Reliability	Mandate in the 10 years approval to operate and the City of Edmonton Drainage Services Master Plan 2004 – 2014 Implementation and strategies requirements, city-wide strategy commits, customer support and services necessary to commission, repair, upgrade, and mitigate the environmental impacts of the city's sewerage and drainage systems, etc.
	Requirement	Contract documents and specifications, project requests, proposal, 10 years approval to operate and the City of Edmonton

		Drainage Services Master Plan 2004 – 2014 Implementation and strategies requirements, etc.
	Resource	Resources, resources management, staff, plans, training, research, human resource, etc.
	Service	High-quality services, drainage services
	Stakeholder requirement	Site plan ordinances, subdivision regulations and building codes, real property law, environmental regulations, contract document and specification, etc.
	Standard	ISO international standards (e.g., ISO 9000, 14000, 19011, 45011), design and construction standards, etc.
	System	Quality management system (QMS), safety management systems (SMS), environmental management system, drainage systems, etc.
	System element	City's sewerage, North Saskatoon watershed, management systems, human resources, etc.
	System requirement	Drainage master plan, watershed management plan, area structural plan, city-wide flood prevention projects, stormwater management facilities, natural wetland conservation, low impact development etc.
	System-of-interest	Area development planning: drainage master plan, flood prevention and erosion control, and stormwater quality management
	Trade-off	Work-life balance, motivation and capability, completion of high-quality projects and stakeholder satisfaction, efficiency and quality, etc.

5.4.1.3 Human environment

The human environments include all the human beings but particularly the human users of an artifact (Zeng, 2015). Concepts in the proposed core ontology related to the human environment are summarized in Table 37.

Table 37 Human environment and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Human environment	Acquirer	Land developers
	Customer	Land development customers
	Operator	Drainage services branch
	Organization	Area development planning, drainage planning for land development group, stormwater management group, etc.
	Party	Third party auditors, land developers, land development customers, drainage services, Alberta regulators, roadway constructors, etc.
	Stakeholder	City of Edmonton, Province of Alberta, public services, etc.
	Supplier	Supplier, drainage design & construction, environmental planning, strategic planning of drainage planning, environmental monitoring of drainage services, private development, sustainable development of the office of biodiversity, etc.
	User	Citizens (Edmonton residents), public

5.4.1.4 Design process

Table 38 Design process and PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Design process	Activity	General supervisor workflows, Green infrastructure & environmental compliance group workflow, etc.
	Process	Drainage planning for land development, stormwater management, green infrastructure & environmental compliance.
	Quality management	Stormwater quality management, quality management.

The design process are the activities (i.e., environment analysis, conflict identification, and solution generation) executed to change an existing environment to a desired one by creating a new artifact into the existing one (Zeng, 2015). Concepts in the proposed core ontology related to the design process are summarized in Table 38.

5.4.1.5 Life cycle

Life cycle are phases (stages) occurring in the life of a product (e.g., design, manufacturing, sales, transportation, use, maintenance, and recycle) (Z. Chen & Zeng, 2006). Concepts in the proposed core ontology related to the life cycle are summarized in Table 39.

Table 39 Life cycle and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Life cycle	Life cycle	Life cycle, feasibility study, site analysis, proposal, etc.
	Life cycle model	SIPOC (Supplier, Input, Process, Output, Customer), model suggested in ISO 9001.
	Stage	Planning
	System life cycle processes	Land development applications and amendment, developing, reviewing and approving drainage master plan, watershed management plan, and area structural plan; during urban planning and design development process in the City of Edmonton

5.4.2 Data analysis: discussion

This chapter proves that the concepts in the proposed core ontology are valid and necessary to represent the domain of land development. Evidence of proof is summarized for EBD root concepts and concepts in the proposed core ontology from Table 34 to Table 39. Therefore, each concept is valid and needed to communicate and understand the context of land development, more specifically area development planning. As a result, the proposed core ontology can be interpreted a valid minimum information model to communicate and understand the context of land development.

In general, the subjective method of characterization enables to allocate the same concepts in more than one concept in the proposed core ontology. This observation triggers to think that it is important to elaborate in specific attributes or properties needed to characterize the concepts in the proposed core ontology. An alternative approach may be to evaluate the feasibility of reducing the number of concepts in order to remove ambiguities in characterizing subjectively the concepts. A foreseen disadvantage of this approach is to remove important concepts in the context of requirements and system life cycle processes. Solving the challenge to have an effective and efficient characterization of concepts is an issue that shall be investigated as future work.

5.5 Conclusions

Area development planning (ADP) is a complex engineering design endeavour where simultaneous evolution of requirements and solutions can be appreciated. The case study to develop a TQMS for ADP proves that EBD root concepts and the concepts in the proposed core ontology are effective to communicate and understand land development, subsequently the broad context of requirements in this kind of engineering projects. All these concepts are implicit in engineering communication during area development planning. Hence, the concepts conform a common vocabulary during area development planning. These concepts will increase the likelihood to improve communication and understanding during area development planning projects. So, the proposed core ontology can be interpreted as a valid minimum information model to communicate and understand the context of land development.

There are limitations in data analysis. One limitation is that the characterization of concepts was not exhaustive. Exhaustive characterization of the concepts may help to interpret the relative importance of each concept. The relative importance of each concept provides guidance about where to prioritize more attention while communicating and understanding requirements in land development. At the current stage of development of the ontology, it was considered more important to identify the right concepts than identifying their relative importance. The right concepts shall be understood properly before trying to understand their relative importance. The rest of case studies will seek to understand the concepts more properly from different engineering domains, while future work may involve defining the relative importance of each concept. In addition, future work needs to investigate specific system life cycle analyses and communication mechanism during land development projects. Finally, future work can also try to tackle the identified problems in characterization discussed in Section 5.4.2.

Chapter 6: Case study 2 - Integrating learning through design methodologies in aircraft design

6.1 Introduction

The contribution of this chapter is to validate the proposed core ontology in Chapter 4. To achieve the needed validation, this chapter employs a case study titled *Integrating learning through design methodologies in aircraft design* as a source of content analysis to facilitate retrospection. The objective of this case study was to *"integrate learning through design methodologies in aircraft design"*. This chapter corresponds to *Integrating learning through design methodologies in aircraft design* highlighted in Fig. 22.

To validate the proposed core ontology, the rest of the chapter is organized as follows. Section 6.2 presents a general background in the context of integrating learning through design methodologies in aircraft design. Section 6.3 presents data collection employing EBD methodology. Section 6.4 discusses data analysis. Finally, Section 6.5 ends with conclusions.

6.2 General background

This section introduces a general background of several topics. Section 6.2.1 describes the importance of the aviation industry. Section 6.2.2 defines aircraft design. Section 6.2.3 defines learning. Section 6.2.4 defines the meaning of a design methodology. Finally, Section 6.2.5 overviews the integration of learning through design methodologies in aircraft design.

6.2.1 Aviation industry

Aviation is one of the most global industries connecting people, cultures, and businesses across continents (Industry High Level Group, 2017, p. 8). Global aviation means 62.7 million jobs supported, 3.5% of the world's gross domestic product (GDP) in 2014, and USD$2.7 trillion in economic impact (Industry High Level Group, 2017, p. 9). Aviation has continued to expand as described in Fig. 64. The aerospace sector to support the aviation expansion will require a decisive and coordinated effort to strengthen and expand the supply of skilled and experienced workers and professionals to capitalize in new market opportunities (Aerospace Review, 2012). Table 40 summarizes four expected outcomes to maximize workplace entry-level skills of Canadian aerospace candidates.

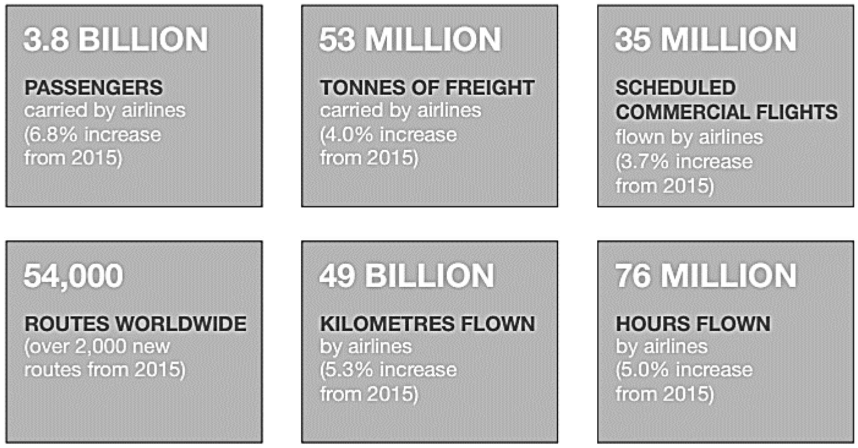

Fig. 64 Aviation expansion from 2015 to 2016 (Industry High Level Group, 2017, p. 8)

Table 40 Expected outcomes to maximize workplace entry-level skills of Canadian aerospace candidates by Aerospace Review (2012, p. 8)

#	Expected outcomes
1	Ensure the competencies of new entrants are aligned with industry requirements and keep pace with rapid technological changes
2	Ensure that industry has access to the right skills at the right time to meet the forecasted demand for skilled labor, particularly in light of the aging workforce
3	Increase productivity and competitiveness by reducing the time it takes for new graduates from university and trade schools to begin adding value to an organization
4	Effectively capture and transfer the knowledge of older members of the workforce to new entrants before this knowledge is lost due to retirement

6.2.2 Aircraft design

An aircraft is any machine that can be supported for flight in the air by buoyance or the effects of the air against its surfaces (Tomsic, 1998). Examples of types of aircrafts are airplanes, helicopters, balloons, and gliders (Hoffman, 2017). Aircraft are composed of systems and subsystems. Aircraft systems are major components of the aircraft which operate from a common source of power, provide a common power source to similar powered components, or perform a major function encompassing lesser functions or components (Tomsic, 1998). Examples of aircraft systems are hydraulics, electric systems, flight control systems, avionics, engine power systems, fuel systems, and all-weather systems (Tomsic, 1998). On the other hand, aircraft subsystems are lesser systems that are components of aircraft systems (Tomsic, 1998). For example, subsystems of the hydraulic system include landing gear, brakes, wing flaps, nose wheel steering, and speed brakes (Tomsic, 1998). Selected systems and subsystems, especially for an airplane flight control system[43], are generically illustrated in the left side of Fig. 65. The right side of the figure presents the major components of a helicopter.

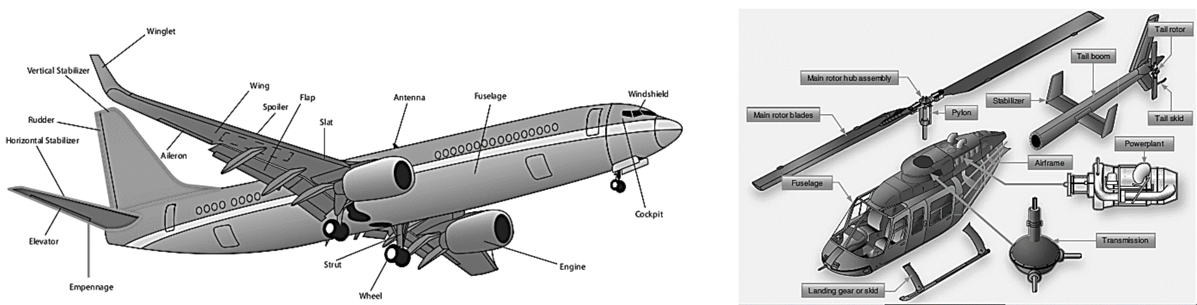

Fig. 65 Examples of aircrafts: Airplane diagram (left) (NASA, 2010, p. 3), and a helicopter with its major components (right) (Federal Aviation Administration, 2012, pp. 1-42)

All aircrafts are designed. Design is a process, usually iterative, by which the details of a system are selected, analyzed, and documented in order to produce a system that meets a specified set of operation criteria (Tomsic, 1998). The definition of design is composed of two components: a process and systems. The process (aka design process) creates a system or an item from a set of requirements (Tomsic, 1998). A system (aka design) is the result of the design process. The ultimate goal of aircraft design is to have the idea, make drawings, calculate data, etc., with the intention of producing an aircraft that meets a specified set of operation criteria.

Operation criteria of designs conform to characteristics. Characteristics may refer to product or service, which combined are known as quality characteristics. Typical product and service

[43] A flight control systems is a system that includes all aircraft subsystems and components used by the pilot or other sources to control one or more of the following: aircraft flight path, attitude, airspeed, aerodynamic configuration, ride, and structural modes (Tomsic, 1998).

characteristics are listed in Table 41. In general, an entire aircraft, systems, and subsystems have their own characteristics.

Table 41 List of typical product and service characteristics (Hoyle, 2001, p. 29)

Type	Characteristics
Product	Accessibility, availability, appearance, adaptability, cleanliness, consumption, durability, disposability, emittance, flammability, flexibility, functionality, interchangeability, maintainability, odour, operability, portability, producibility, reliability, reparability, safety, security, size, susceptibility, storability, strength, taste, testability, traceability, toxicity, transportability, vulnerability, and weight.
Service	Accessibility, accuracy, courtesy, comfort, competence, credibility, dependability, efficiency, effectiveness, flexibility, honesty, promptness, responsiveness, reliability, and security.

6.2.3 Learning

Learning has several definitions and interpretations. For example, Heery and Noon (2017) defines learning as the process through which individuals acquire knowledge, skills, and attitudes achieved through experience, reflection, study, or instruction. Colman (2016) defines learning as the act or process of acquiring knowledge or skills, or knowledge gained by study resulting in any lasting change in behavior. The U.S. Department of Transportation: Federal Aviation Administration (2008a, pp. 2-2) proposes different definitions of learning as follow: 1) A change in the behavior of the learner as a result of experience. The behavior can be physical and overt, or it can be intellectual or attitudinal, 2) the process by which experience brings about relatively permanent change and behavior, 3) the change in behavior resulting from experience and practice, 4) gaining knowledge or skills, or developing a behavior, through study, instruction, or experience, 5) the process of acquiring knowledge or skill through study, experience, or teaching. It depends on experience and leads to long-term changes in behavior potential. Behavior potential describes the possible behavior of an individual (not actual behavior) in a given situation in order to achieve a goal, 6) a permanent change in cognition resulting from experience and directly influencing behavior. As there are several definitions and interpretations of learning, it is imperative to adopt one interpretation.

Considering that there are several definitions and interpretation of learning, this case study adopts the guidance of EBD theory (Zeng, 2011, 2015). EBD theory defines learning considering three factors: knowledge, skills, and affect (see Table 42). In aviation, the three factors are sometimes referred as the domains of learning (i.e., cognitive – thinking, affective – feeling, and psychomotor – doing) (see Fig. 66). Other researchers in the engineering community interpret the three factors as the Bloom's taxonomy of educational objectives (Crawley, 2001, pp. B1-B7). The three factors are implicit or explicit in the previous definitions of learning. The three factors agree with the definition of competencies (i.e., knowledge, skills, abilities, and work values) needed to perform aerospace engineering job efficiently and successfully (Aerospace Review, 2012, p. 6). The three factors are intended to be effective learning variables to achieve desirable changes in behavior. Desirable changes in behavior are expected to maximize the workplace entry-level skills of Canadian aerospace candidates.

Table 42 Definition of knowledge, skills, and affect (T. A. Nguyen & Zeng, 2012; S. Tan, Marsden, & Zeng, 2016)

Factor	Definition
Knowledge	Knowledge is influenced by the structure of knowledge and the availability of cognitive resources. Examples include synthesis knowledge, evaluation knowledge, critical requirements, primitive design solution, partial design solution, etc.
Skill	Skills refer to the thinking styles, thinking strategy or reasoning methods. Examples are: identify, search for, generate, evaluate, analyze, redefine, and recompose.
Affect	Affect refers to emotion, and any state associated with feeling such as tiredness. Affect is also affected by personality, attitude, belief, motive and stress.

Cognitive	Affective	Psychomotor
Knowledge	Attitude	Skills
Recall information	Awareness	Observation
Understanding	Respond	Imitation
Application	Valuing	Practice
Analyze	Organization	Habit
Synthesize	Integration	
Evaluate		

Fig. 66 Overview of the three domain of learning (U.S. Department of Transportation: Federal Aviation Administration, 2008a, pp. 2-12)

6.2.4 Design methodologies

A design methodology is a systematic approach to creating a design consisting of the ordered application of a specific collection of tools, techniques and guidelines (ISO/IEC/IEEE, 2017). According to the previous definition, design methodologies can be interpreted as processes, methods and tools to support a design process in order to achieve the creation of a desired design outcome (Anderson, 2006; Estefan, 2007; Hubka, 1983; Pahl et al., 2007). The meaning of processes, methods and tools is defined in Table 43. The design process refers to tasks and timeline to achieve the creation of the desired design outcomes (i.e., expected deliverables). In general, deliverables can be documents (e.g., requirements, WBS, schedules, engineering bill of materials, manufacturing bill of materials, production site locations and layouts, life cycle costing, etc.), prototype hardware, or prototype software (Butterfield et al., 2007; R. Curran, Kundu, Raghunathan, & Eakin, 2001).

The study of design methodologies has evolved since the 1940's through different regions such as Europe (e.g., Germany, Switzerland, Great Britain, France, Italy, and Scandinavia), North America (USA and Canada), Euro-Asia (e.g., Russia), Asia (e.g., Japan), and other international developments (Chakrabarti & Blessing, 2016; Eder, 2012). The study of design methodologies has led to the proposal of a plethora of design methodologies (Estefan, 2007; Fu, Yang, & Wood, 2016; Hubka, 1983; Pahl et al., 2007; Yang, 2007), which arguably creates confusion and hinders understanding. To solve this problem, systems engineering is adopted in this case study as an interdisciplinary approach and means to enable the realization of successful systems (INCOSE, 2015, p. 265). Mavris and Pinon (2012), and Price, Raghunathan, and Curran (2006) demonstrate that systems engineering exhibits strong similarities with the aircraft design process, as both build on decomposition, synthesis, and verification to achieve successful systems.

Table 43 Definition of process, method and tool (Hubka, 1983; Hubka & Eder, 1987)

Concept	Definition
Process	A process may be structured into more or less complex partial processes, phases, and detailed design steps. Processes results in changes in the state of information (e.g., from requirements to description of systems).
Method	A method refers to rules of designer's behavior and methodical directions to progress processes in a planned and methodical way. Methods may also involve regulating the collaboration between engineering designers with available technical means (e.g., computers), technical knowledge (e.g., science, alternative principles, know-how), and environment conditions (e.g., working conditions).
Tool	A tool is a technical means to perform the method. For example, cost estimating during design where designers need to obtain cost estimates on alternative ways of solving some problems sufficiently quickly and accurately to influence their decisions requires the use of cost estimation tools.

Systems engineering is usually combined with more specific but also generic design methodologies such as Quality Function Deployment (QFD), and Theory of Inventive Problem Solving (TRIZ) (Eder, 2001; Eversheim, 2009; Gudmundsson, 2014; Hsu, 2006; Kamarudin, Ridgway, & Hassan, 2015; Lu, Gu, & Spiewak, 2004; Mavris & Pinon, 2012; Price et al., 2006). Considering the objective of the case study, learning shall be integrated to design methodologies (i.e., systems engineering) in order to support aircraft design. Such integration is investigated in this case study by using EBD theory and methodology.

6.2.5 Integrating learning through design methodologies in aircraft design

Environment-based design (EBD) (Zeng, 2011, 2015) is a systematic design methodology under research and development at Concordia University by Professor Yong Zeng. EBD has reported positive research attempts in aircraft design (Deng, Huet, Tan, & Fortin, 2012; S. Tan, Zeng, Huet, & Fortin, 2013). EBD has also suggested potential integration with design methodologies such as TRIZ, and axiomatic design (Dubois et al., 2012). EBD methodology has the components of design methodologies: processes, methods, and tools. In general, processes correspond to the activities (i.e., environment analysis, conflict identification, and solution generation) in EBD methodology. Integration of learning into EBD is implicit in the methodology. The methodology suggests three activities: environment analysis, conflict identification, and solution generation (Zeng, 2011, 2015). The activities are guided by a step-by-step process in order to facilitate knowledge management through question and semantic modeling. The step-by-step process through questions and modeling is considered as skills. Knowledge management (aka acquisition, recording, integration, and control) is considered as knowledge. Questions and modeling facilitate acquisition, recording, integration and control of knowledge. The third factor in learning, besides knowledge and skills, is affect. Affect is investigated in EBD theory based on stress management during the step-by-step process (P. Nguyen, Nguyen, & Zeng, 2015a, 2015b; P. Nguyen et al., 2018a, 2018b; T. A. Nguyen, 2016; T. A. Nguyen et al., 2013; T. A. Nguyen & Zeng, 2014, 2017; S. Tan et al., 2016). Stress management seeks to find the optimal stress level that leads to higher design performance. Stress management is conceptually defined in Fig. 67, which suggests that work overload and underload harm performance, while the optimal stress level maximizes performance. Stress is a psychological and physical strain or tension generated by physical, emotional, social, economic, or occupational circumstances, events, or experiences that are difficult to manage or endure (Colman, 2016). More specifically, stress management in EBD theory is investigated under the scope of mental stress (i.e., cognitive psychology) (Bourne & Yaroush, 2003). Mental stress is defined by the relationship of workload and mental capability (T. A. Nguyen, 2016, p. 15). Workload is the external load assigned to a person whereas mental capability is the person's ability to handle the external load at that time. Workload comes from the environment (e.g., work environment defined by the physical, chemical, biological, organizational, social and cultural factors surrounding a worker). Mental capability comes from knowledge, skills, and affect. The relationship of workload and mental capability results in perceived capability and perceived workload. The result leads to the quantification of mental stress. Conceptually, the relationships between workload, mental capability, and mental stress are illustrated in Fig. 68. Affect through stress management is beyond the scope of this research, but it may play a significant role in learning.

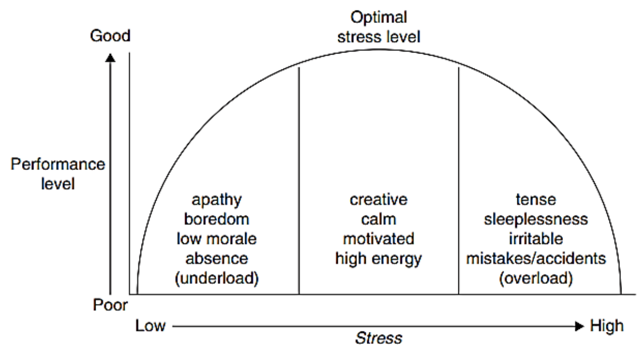

Fig. 67 Optimizing stress: the relationship between work overload/underload, performance and health (Bourne & Yaroush, 2003, p. 41; Weinberg, Sutherland, & Cooper, 2010, p. 79)

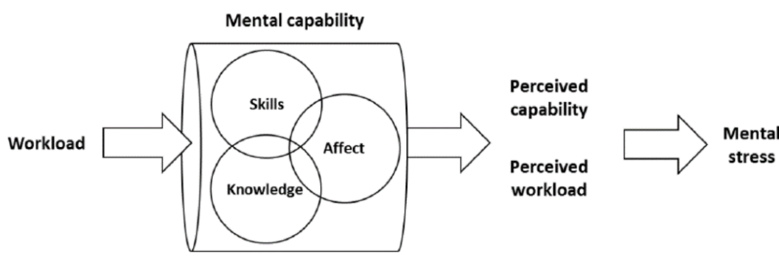

Fig. 68 Relationship between mental capability, workload, and mental stress (T. A. Nguyen, 2016, p. 17)

This case study integrates learning through EBD methodology in aircraft design. In particular, learning is modeled through workload. Workload is aircraft design which refers to the design process and the results (systems and subsystems) of the design process. Specifying workload as aircraft design is the input to subsequently define knowledge, skills, and affects needed to quantify mental stress. Such quantification is useful to manage (plan, distribute, execute, and control) workload in aircraft design projects.

6.3 Data collection

My participation in aircraft design related project started in summer 2014 in a collaborative industrial project with initial kick-off meeting on July 21st. Since that date, the author has been collaborating directly and indirectly in aircraft design related projects. One of the original assignments in this project was to capture customer requirements and to link them to product characteristics. A direct industrial partner for this assignment was Bombardier Aerospace. Considering that a nondisclosure agreement was signed related to the assignment, real data cannot be published. A second assignment was to investigate which design methodologies are effective to support a capstone project in aerospace design engineering under the umbrella of NCADE (i.e., NSERC Chair in Aerospace Design Engineering). This assignment started on October 2016 and ended with a couple of publications in the subject presented in Summer 2017 (Gutierrez, Liu, Singh, Marsden, & Zeng, 2017; Taheri, Gutierrez, Zeng, & Marsden, 2017). This case study, founded on the experience of the assignments, is expected to illustrate lesson learnt from the author in the context of customer requirements and product characteristics. Information in this case study is created based on the author's current understanding from learning perspective in the subject of aircraft design. This understanding has not been applied in any industrial context.

Data collection employs EBD methodology. Thus, data collection executes environment analysis (Section 6.3.1), conflict identification (Section 6.3.2), and solution generation (Section 6.3.3). The rest of this section presents the result of data collection.

6.3.1 Environment analysis

Environment analysis follows the same strategy applied for developing a TQMS in Chapter 5 and designing the right healthcare decision support in Chapter 7. Environment analysis supports data collection through the question asking strategy in EBD methodology (Zeng, 2011). The major tools in EBD methodology to implement the strategy are: ROM (Zeng, 2008) and the question asking generation process (Wang & Zeng, 2009).

The question-asking strategy started by creating a ROM representation from the objective of the case study, i.e., *integrate learning through design methodologies in aircraft design.* Based on the objective, the ROM representation in Fig. 69 was created. The ROM representation was used to generate questions. The questions were classified into 4 groups: 1) aircraft design 2) learning, 3) design methodologies, and 4) integrating learning through design methodologies in aircraft design. Selected questions with their respective assigned groups are defined in Table 44. Table 44 also defines the sections where the questions are answered in this chapter.

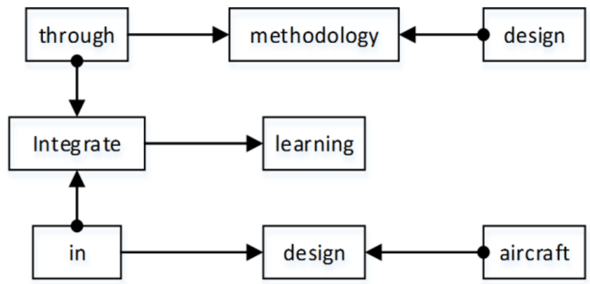

Fig. 69 ROM representation for the case study objective

Table 44 Selected questions and assigned groups

Group	Generated question	Section
Aircraft design	1. What is aircraft? 2. What is design? 3. What is aircraft design?	Section 6.3.1.1
Learning	4. Why to integrate learning in aircraft design? 5. What is learning? 6. What is to integrate learning in aircraft design? 7. Who integrates learning in aircraft design? 8. Where to integrate learning in aircraft design? 9. When to integrate learning in aircraft design? 10. How to integrate learning in aircraft design?	Section 6.3.1.2
Design methodologies	11. What is methodology? 12. What is design methodology?	Section 6.3.1.3
Integrating learning through design methodologies in aircraft design	13. How to integrate learning in aircraft design through design methodologies?	Section 6.3.1.4

6.3.1.1 Aircraft design

The questions corresponding to this section in Table 44 have been preliminary answered in Section 6.2.2. In this section, more details are elaborated. The goal of this section is to depict the general idea about the scope of aircraft design especially at the conceptual level.

6.3.1.1.1 What is an aircraft?

An aircraft is any machine that can be supported for flight in the air by buoyance or the effects of the air against its surfaces (Tomsic, 1998). Aircrafts in this case study refer to civil airplanes (e.g., regional propellers, regional jet aircraft, narrow body jet aircraft, and wide body jet aircraft) (Torenbeek, 2013, pp. 33-35). Civil aviation includes over 416,000 aircrafts flying worldwide today (General Aviation Manufacturers Association, 2016). General facts about civil airplanes can be found in Appendix E (Section E.2). Civil airplanes are composed of systems and subsystems. Civil airplane systems can be identified from the taxonomy defined by ATA 100 specification (Scholz, 2003, p. 4). The taxonomy is illustrated in Fig. 70. Level 1 in the figure defines the most abstract case of the aircraft system. The aircraft systems refer to the aircraft, training, support, facilities, and personnel. Level 1 is beyond the scope of this case study. Level 2 defines civil airplane systems, and level 3 defines their corresponding subsystems. In general, level 2 systems can be categorized into the airframe (i.e., aircraft structure), the power plant (i.e., the engines), and the rest of systems (i.e., the equipment – e.g., flight control systems) (Scholz, 2003, p. 1). An example of such system category is presented by Criou (2007). Depending on the type of system category, years to maturity of technology varies. Using the scale of nine technology readiness level (TRL) proposed by NASA, the average years of maturity for airframes, engines, and flight control systems at each level is specified in Appendix E (Section E.2). Civil airplane systems are a combination of interrelated subsystems arranged to perform a specific function on the aircraft (Scholz, 2003, p. 3). After one or several prototype aircraft are designed and manufactured, they go through a series of certification tests in order to show compliance with the certification requirements (Scholz, 2003, p. 5). Compliance for certification can be proved by analysis, ground, or flight test (Scholz, 2003, p. 5). The certification of one or several prototype civil airplanes leads to the issuance of a type certificate. Civil airplanes in series production have to demonstrate airworthiness and conformity with the prototype aircraft. In service, civil airplanes have to be maintained according to an agreed maintenance schedule to prove continuous airworthiness. Certification is intended to assure safety and reliability of the civil airplane systems, which are an integral part of the safety and reliability of the whole civil airplane (Scholz, 2003, pp. 6-13). Integration of civil airplane systems creates its own challenges to aircraft design involving a variety of disciplines (Baalbergen, Kos, Louriou, Campguilhem, & Barron, 2017; Ciampa & Nagel, 2016; Defoort et al., 2012; Piperni, Abdo, Kafyeke, & Isikveren, 2007; Ying, 2016), see

Fig. 71. Depending on the employed disciplines, design facilities may vary. For example, Fig. 72 is the integrated multidisciplinary design facility at the Europe Space Agency. The design facility indicates the simultaneous use of different disciplines for aircraft design purposes. An alternative team structure which may implied a different design facility is illustrated in Fig. 73. The team structure in the figure is the type of organization used to design the Boeing 777.

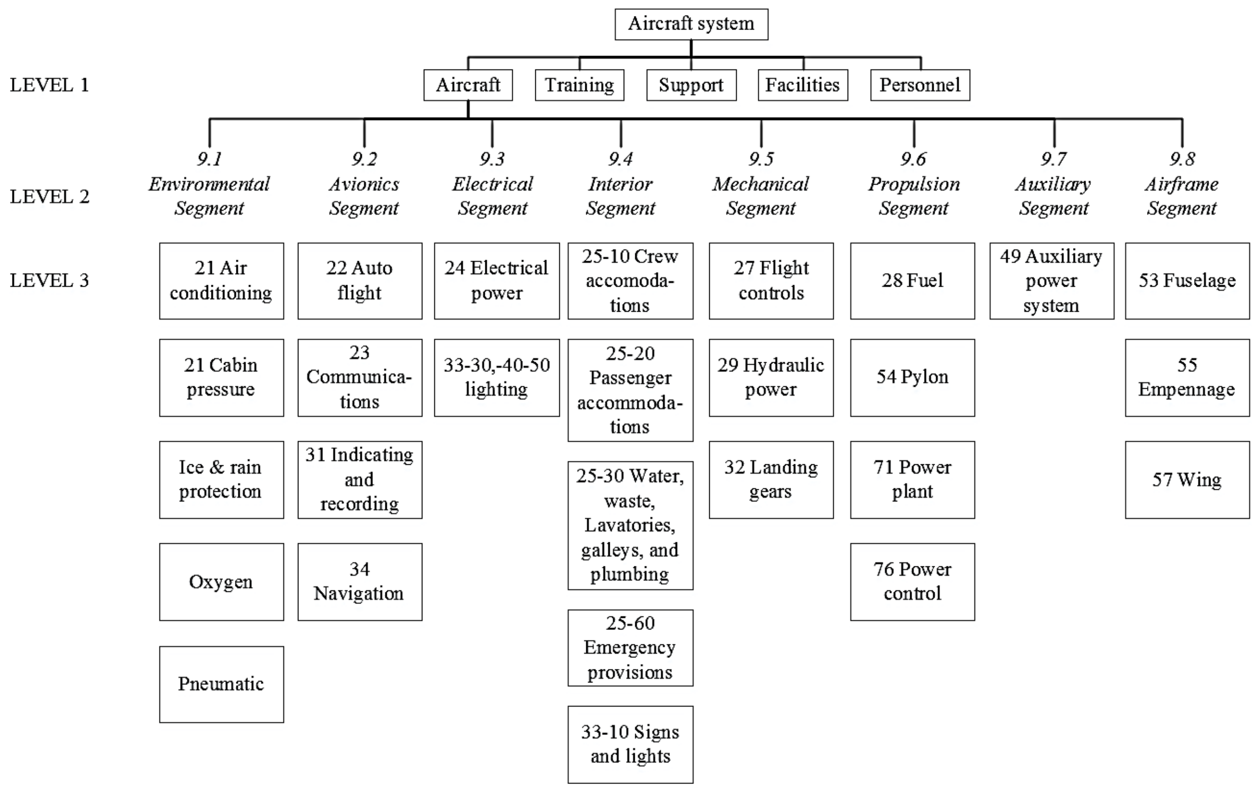

Fig. 70 Generic aircraft system architecture and ATA chapter correlation, adapted from (Jackson, 2015, p. 12)

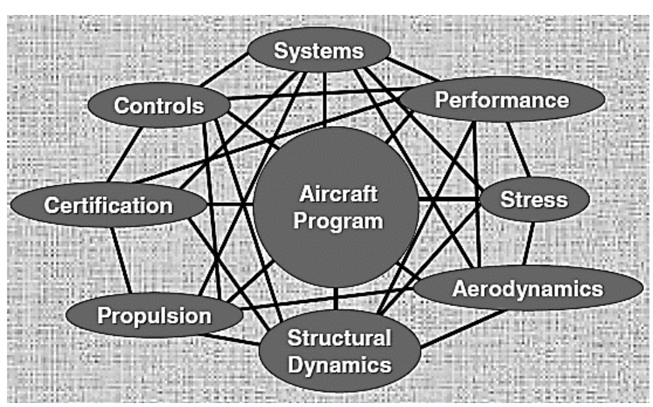

Fig. 71 Complex interaction of various disciplines in civil airplane design (Kafyeke, Abdo, Pépin, Piperni, & Laurendeau, 2002)

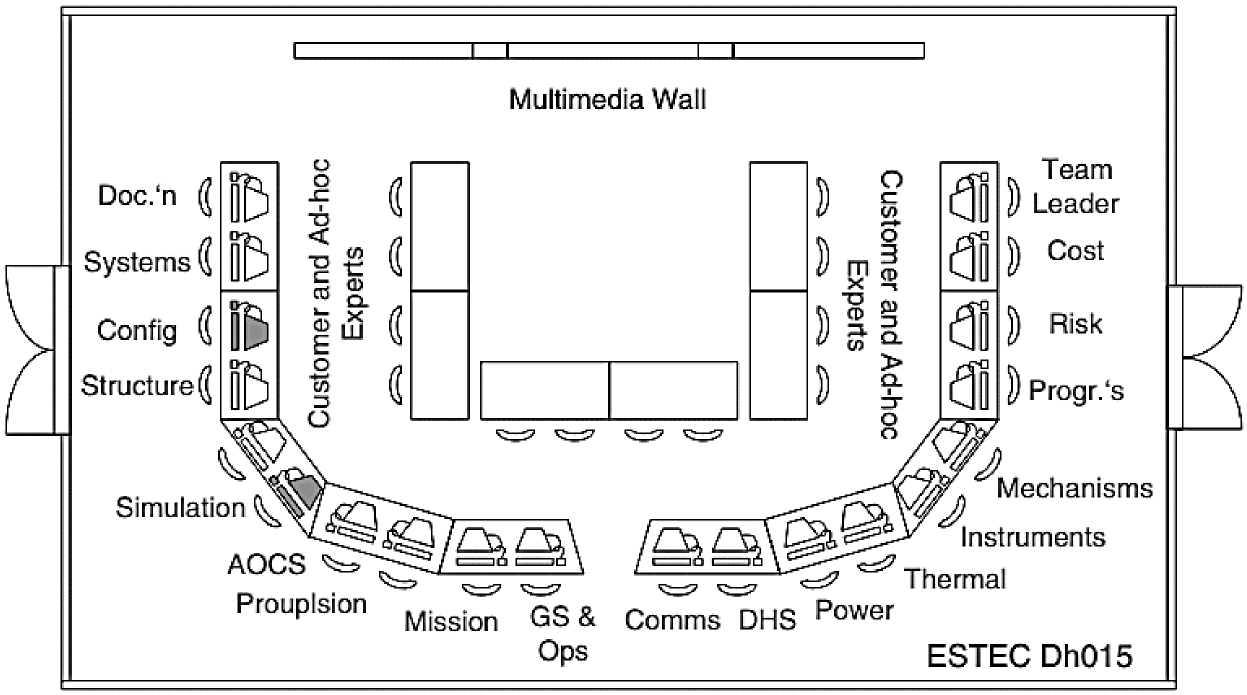

Fig. 72 The integrated multidisciplinary design facility at the Europe Space Agency (Richard Curran, Zhao, & Verhagen, 2015)

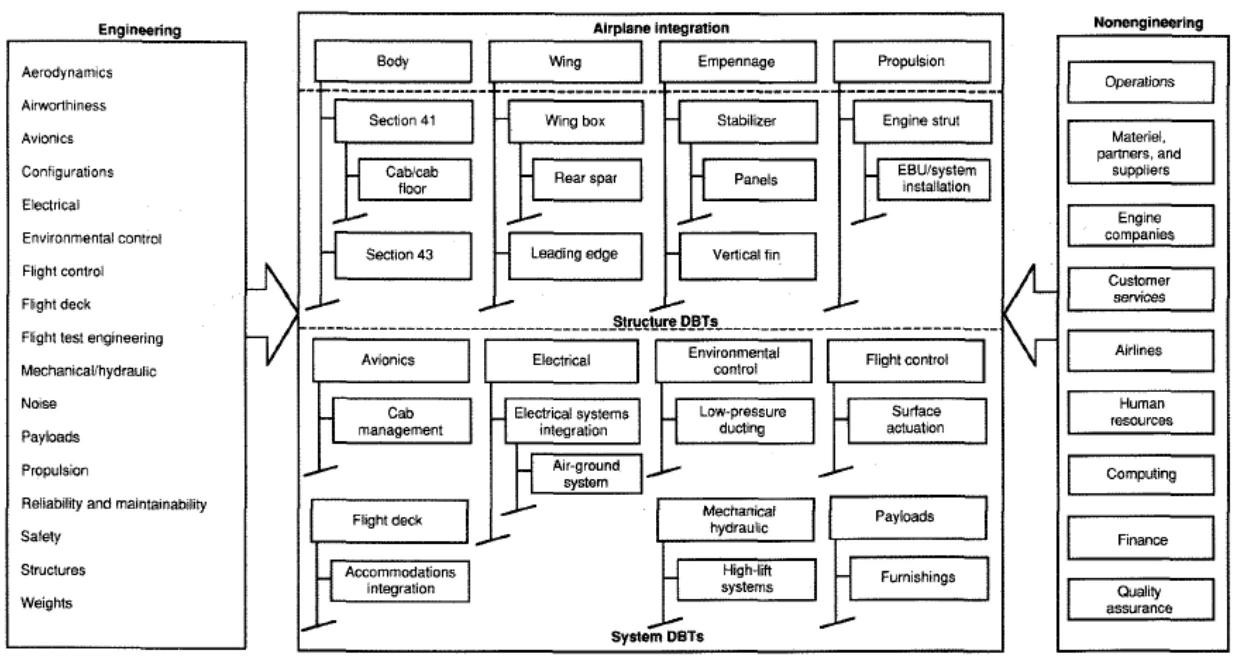

Fig. 73 Design-build team structure for the Boeing 777 development program (Breuhaus, Fowler, & Zanatta, 1996)

6.3.1.1.2 What is design?

Design in this case study refers to the civil airplane system & subsystems, and the airplane design process. Civil airplanes systems and subsystems were defined in Fig. 70. The function of the level 2 systems in the figure are defined in Table 45. Researchers may define these functions differently (Chiesa, Fioriti, & Viola, 2012; Scholz, 2003). Therefore, further effort shall be done to validate the correct and complete definitions of the functions in Table 45. The system and their function get matured along the design and development process. This process varies from company to company. For example, Fig. 74 defines a high-level life cycle process for civil airplane design and development. Fig. 75 is a zoom-in to the development stage in Fig. 74. Fig. 75 indicates that Boeing and Airbus define their development process differently. Such differences may also be found in the alternative life cycle models in Appendix E (Section E.3). The differences may hinder communication between stakeholders; thus, it is imperative to define and agree about the employed life cycle model and supporting organizational structure.

Table 45 Level 2 systems in Fig. 70 and their functions, extracted from (Moir & Seabridge, 2013)

System	Function	Page
Environmental segment	To provide heating and/or cooling air for passengers, crew, and avionics equipment.	272
Avionics segment	To provide cockpit displays and controls, communications, navigation, flight management system, automated landing aids system, weather radar systems, traffic collision and avoidance system, ground proximity warning systems (GPWS) & terrain avoidance warning systems (ATWS), distance measuring equipment, automatic direction finding, radar altimeter, automatic flight control system, air data system, cockpit voice recording, prognostic and health management (PHM), and internal lighting	280-286
Electrical segment	To provide a source of regulated AC and DC power to the aircraft systems via bus bars and circuit protection devices.	268
Interior segment	To provide crew accommodation, passenger accommodation, water, waste, lavatories, galleys, & plumbing, emergency provision, and signs & lights.	275, 277, 278, 279
Mechanical segment	To enable hydraulic systems, flight control systems, and landing gear systems. Hydraulic systems provide a source of high-pressure motive	269, 270, 271

	energy for actuation mechanisms. Flight control systems translate the pilots command into a demand for power to drive primary and secondary control surfaces, to respond to autopilot demands for automatic control and stability. Landing gear systems enable the aircraft to be mobile on the ground, including nose wheel steering.	
Propulsion segment	To provide thrust for the vehicle and to provide a source of off-take power for electrical power generation, hydraulic power generation and air for pneumatic systems and environmental cooling systems.	267
Auxiliary segment	To start the main propulsion system, provision of air and electrical power during ground operations with no engines operating to provide autonomous operation – rapid turnaround.	269
Airframe segment	To support the mass of systems and passengers and carry loads and stresses throughout the structure. To form the whole structure of the aircraft.	22

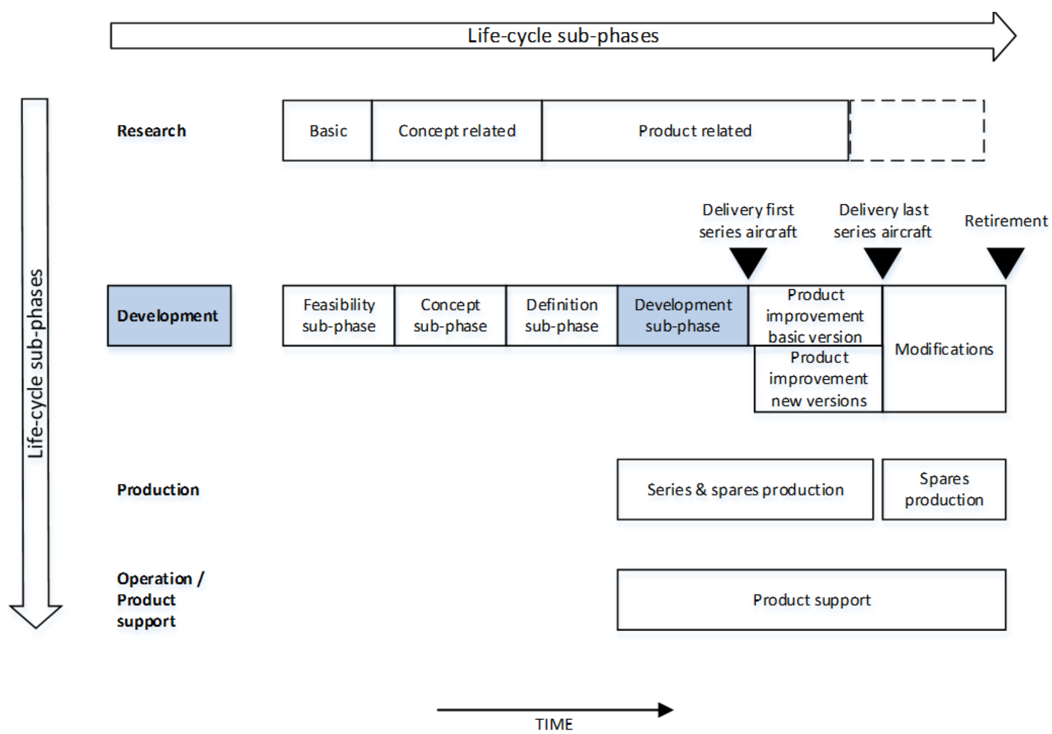

Fig. 74 Life cycle phases for typical commercial aircraft programme with breath (x-axis) and depth (y-axis) phases (Altfeld, 2010, p. 48)

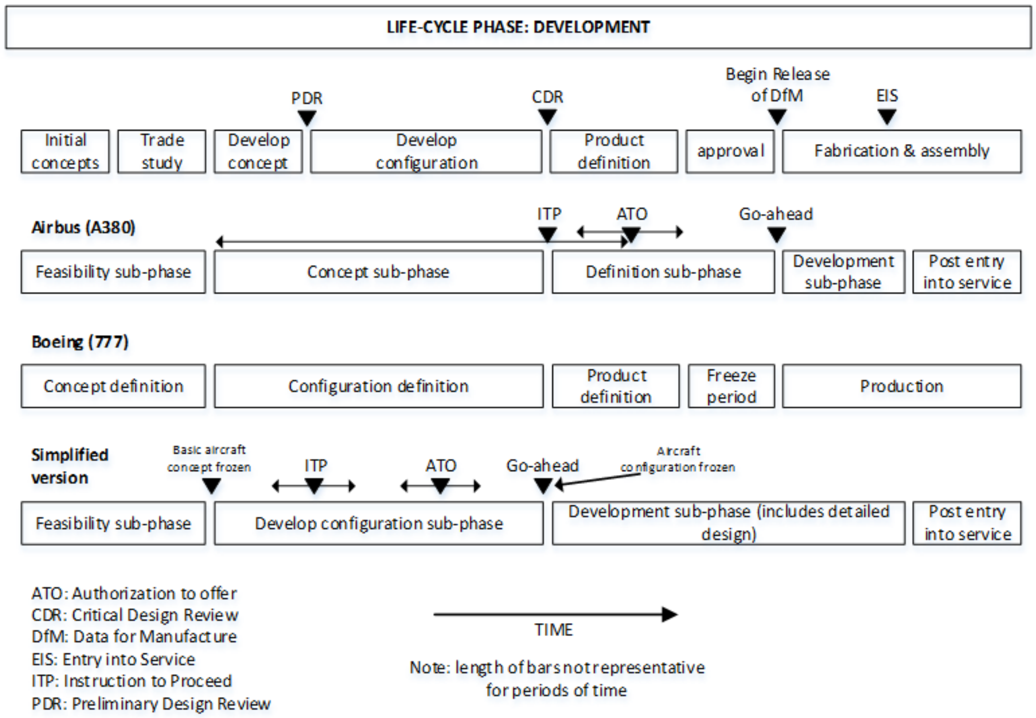

Fig. 75 Phased project planning used for development phase for commercial aircraft: contrasting Airbus 380, Boeing 777, and proposed simplified version (Altfeld, 2010, p. 50)

6.3.1.1.3 What is aircraft design?

The design process of a civil airplane design starts with requirements (Eres et al., 2014; Isaksson et al., 2013). Requirements evolve along the life cycle process employed for design and development. According to Piperni, DeBlois, and Henderson (2013), these requirements are: 1) marketing requirements and objectives, 2) aircraft configuration topology, 3) aircraft-family concept and mission requirements for each family member, 4) aircraft operation and mission profile (speed and altitude schedule), 5) engine architecture, size, and location on the aircraft, 6) system's architecture and layout, 7) fuselage cross section and length(s), cabin configuration(s), structural layout, and wing-to-fuse attachment, 8) aircraft c.g. (center of gravity) envelop, 9) empennage size, location, and type, and 10) high-lift-system type and layout, and 11) technology-insertion strategy. These requirements encompass the scope defined in Fig. 76. The requirements in the figure can be complemented with the following requirements: reliability, producibility, evaluability, maintainability, usability (e.g., comfort), safety (airworthiness for aircraft), crashworthiness, supportability & serviceability, disposability, and legal requirements (Sadraey, 2013, p. 33). Besides comfort, safety, security & reliability, cost and timely delivery as marketing requirements, range (km), number of seats, and payload (kg) have been major driving requirements over time (Altfeld, 2010, p. 53; Dewar, 2018; Di Bianchi, Orra, & Silvestre, 2017; Evrard & McConnell, 2016; Glende, 1997; Isikveren, Goritschnig, & Noël, 2003; Ramesh, Reddy, & Fitzsimmons, 2018; Torenbeek, 2013, pp. 35-36). Changes of range (km), number of seats, and payload (kg) since 1960 can be found in Appendix E (Section E.2). Other important requirements are related to the natural environment (aka environment impacts) especially reduction of emissions (i.e., CO_2, NO_x) and noise during manufacturing, operation, maintenance, and disposal (IATA, German Aerospace Center (DLR), & Georgia Institute of Technology, 2013; Isikveren et al., 2016).

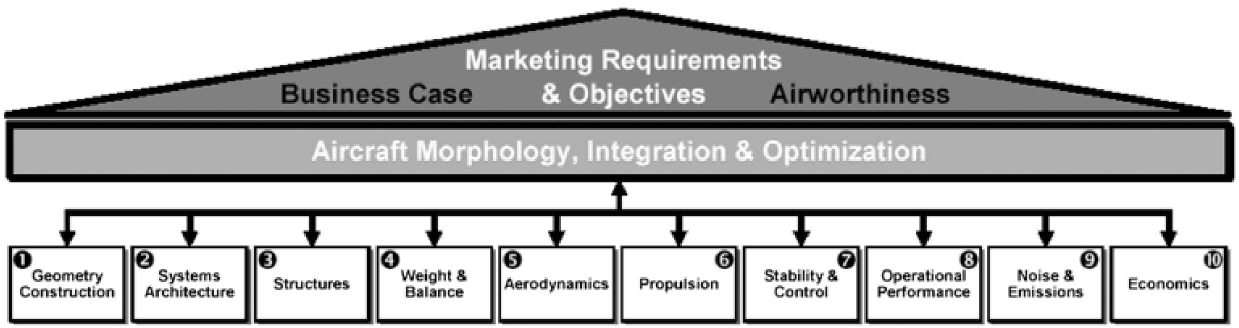

Fig. 76 The complete aircraft product development problem: customer, certification, and integrator requirements transformed into the three macro-disciplines and their associative 10 technical subspace. Note: manufacturability and producibility consolidated into "business case" (Piperni et al., 2007)

The selected aircraft design process and corresponding life cycle model affect the sequence and requirements flow in the design and development of the airplane. A generic model for aircraft design and development is illustrated in Fig. 77. From the figure, it is important to highlight that everything is connected in the design process flowing down requirements from the market until the desired level of details of the airplane system. The idea is also supported in Table 46, which is also discussed by other researchers (Eres et al., 2014; Isaksson et al., 2013). Fig. 76 implies the same idea. The idea facilitates to link requirements to product characteristics. The link is evaluated through reviews (i.e., conceptual design review [CDR], preliminary design review [PDR], evaluation and test review [ETR], and critical (final) design review [FDR]) along the design process (Sadraey, 2013, pp. 34-37). It is beyond the scope of this case study to discuss the selection of the design process. However, some discussion in the subject are provided by Altfeld (2010) and Breuhaus et al. (1996). It is believed that this subject may have a significant impact in the performance of aircraft design.

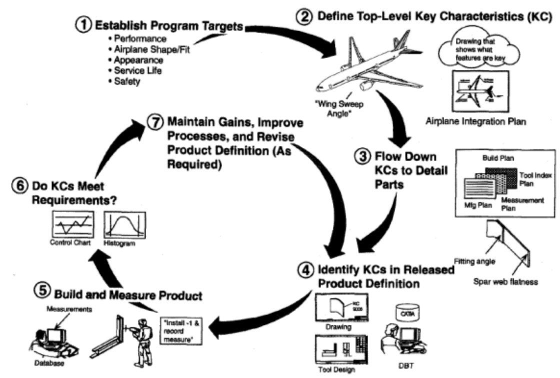

Fig. 77 Generic airplane design model – information flow and traceability (Breuhaus et al., 1996)

Table 46 Value-driven design (VDD) (Cheung et al., 2012)

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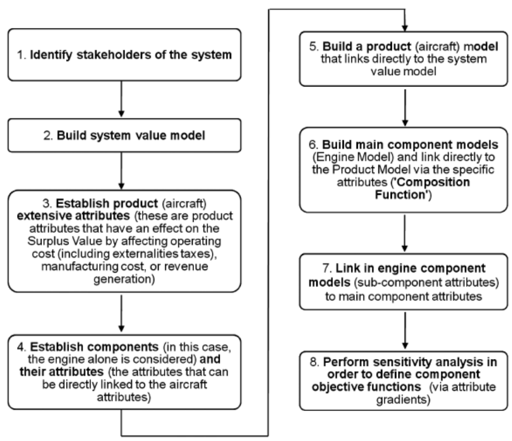
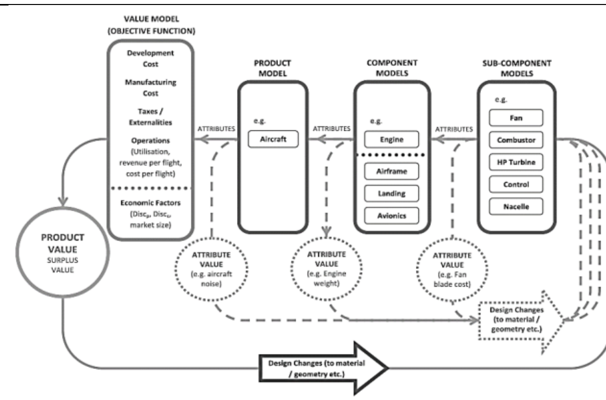
<td>

Generalized VDD modeling process steps</td>
<td>

VDD process (a global optimization of product profitability)</td>
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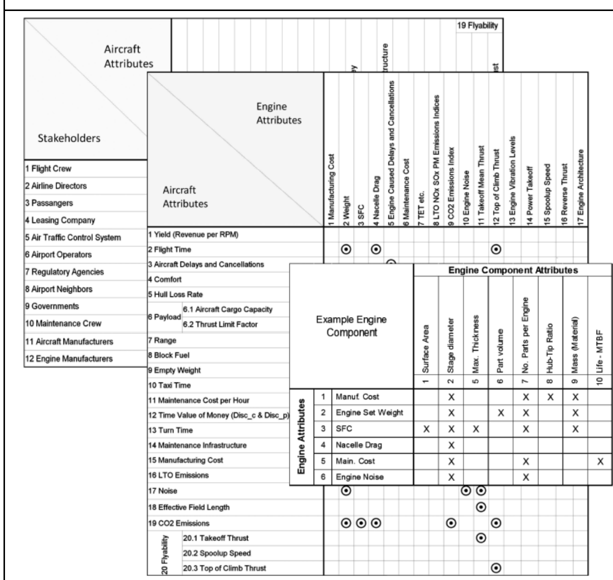
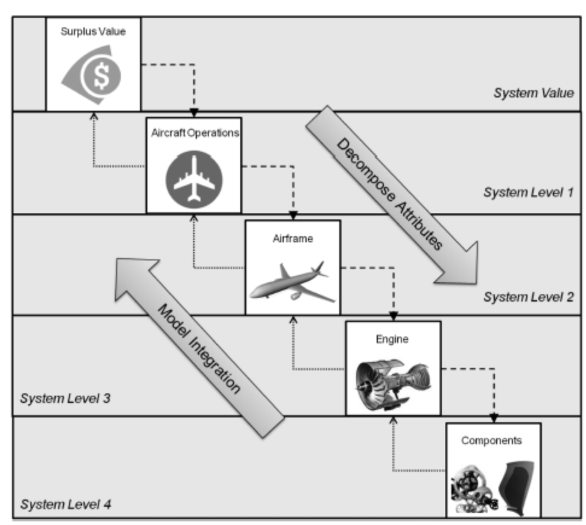
<td>

Identifying attributes and their links</td>
<td>

Aircraft system hierarchy</td>
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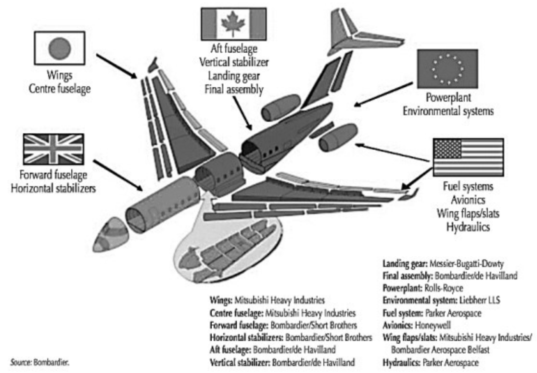
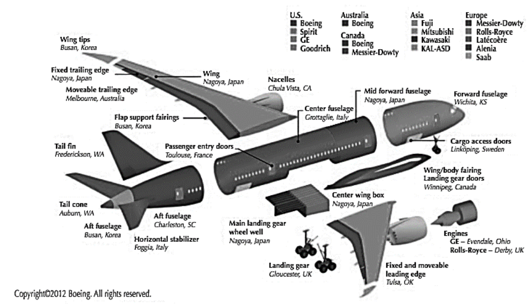
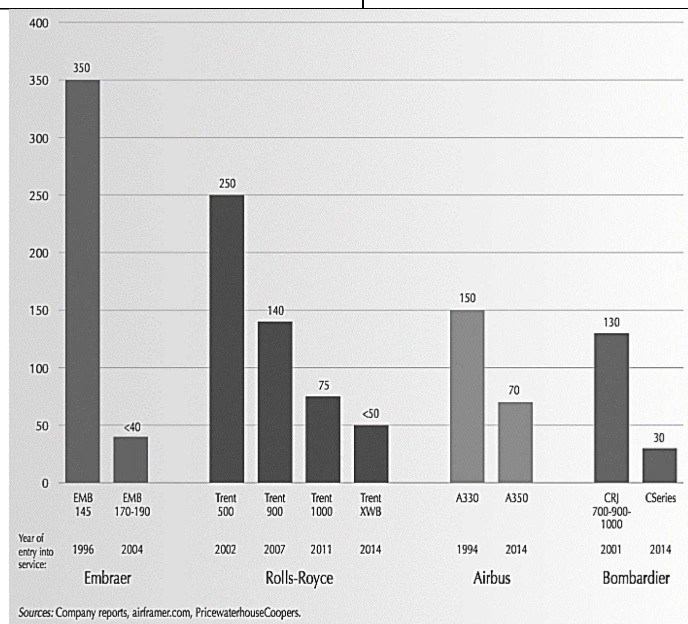
Table 47 Global supply chain of the aerospace industry and trends in supply chain consolidation (Emerson, 2012, pp. 25-26)



Global supply chain for the Bombardier Global Express



Global supply chain for the Boeing 787



Consolidation of supply chains: number of suppliers on selected platforms and systems

The design process of a civil airplane is a complex global activity involving several partners. These partners are stakeholders that can be allocated along the systems & subsystems of the aircraft. For example, Table 47 briefly indicates that several systems & subsystems for a Bombardier Global Express and a Boeing 787 come from countries around the world supplied by different partners. In the context of Canada, Appendix E (Section E.4) defines four major aerospace clusters (i.e., Western Provinces, Ontario, Quebec, and Atlantic Provinces) that design and develop aircraft systems & subsystems. Emerson (2012, p. 14) points out that Montreal's aerospace cluster is the third largest in the world (besides Toulouse and Seattle in the France and

US respectively) and accounts for about half of all Canadian aerospace manufacturing employees. Based on systems & subsystems of a civil aircraft, Appendix E (Section E.4) defines a generic structure and classification of the industry in Canada. The same appendix also describes and exemplifies the main categories of suppliers (i.e., OEM, Tier, 1, etc.) in the generic structure and classification of the industry in Canada. The number of systems & subsystems in aircraft, involved stakeholders (e.g., suppliers), and the required economical investment to design and develop a civil aircraft leads to complexity. Factors leading to complexity are summarized in Fig. 78.

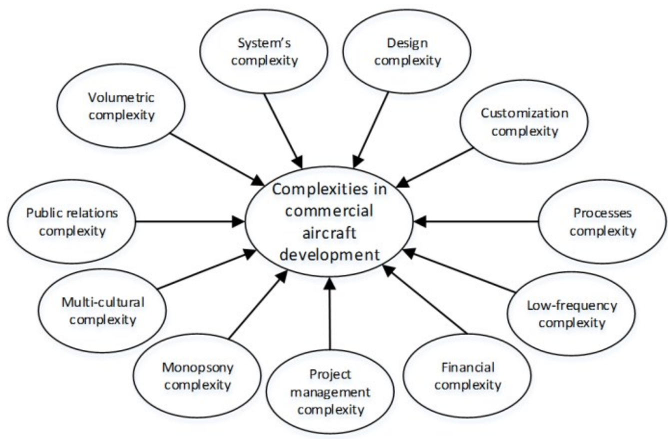


Fig. 78 Complexities in commercial aircraft development, drawn based on Altfeld (2010, pp. 6-21)

The natural environment places significant constraints as implicit requirements to the civil airplane design. The natural environment may affect people (e.g., passengers, crews, and pilots), and the airplane (e.g., corrosion). For example, pressurization of the airplane cabin is necessary in order to protect people against hypoxia (i.e., reduced oxygen or not enough oxygen), particularly is the cabin altitude is maintained at 8,000 feet or below (U.S. Department of Transportation: Federal Aviation Administration, 2016, pp. 7-35). At night, the horizon may be hard to discern by airplane's pilot due to dark terrain and misleading light patterns on the ground (e.g., see Fig. 79). The airplane is also affected by the natural environment (e.g., climate). For example, direct chemical attack and electrochemical attack from the natural environment can be manifested into surface corrosion (U.S. Department of Transportation: Federal Aviation Administration, 2008b, pp. 6-2). Other threats from the natural environment to the airplane comes from meteorological conditions (e.g., pressure, density, temperature, moisture, wind, and engine icing), or animals (e.g., bird strikes) (U.S. Department of Transportation: Federal Aviation Administration, 2016).

Fig. 79 Vision problems at night flights (U.S. Department of Transportation: Federal Aviation Administration, 2016, pp. 17-27)

Finally, the natural environment affects the physics of flight. The physics of flight shall be considered in any aircraft design. Physics of flight includes subjects such as matter, energy, force, work, power, torque, mechanisms & machines, stress, motion, heat, pressure, gas laws, fluid mechanics, sound, the atmosphere, aircraft theory of flight (e.g., aerodynamics), electricity, and magnetism (U.S. Department of Transportation: Federal Aviation Administration, 2008b). The physics of flight shall be understood along the operation of the aircraft (e.g., pre-flight/taxi out, takeoff, climb, cruise, descent, maneuvering, approach, landing, and taxi in) as exemplified in Fig. 80. The physics of flight affect and might vary at each global destination of the aircraft. The physics of flight shall be investigated at the whole aircraft level and at least at system & subsystem levels (Valdivia de Matos, Marques da Cunha, & Viera Dias, 2014). The whole aircraft is related and interacts with the systems and subsystems as conceptually illustrated in Fig. 81. Such conceptualization is needed to prove that the whole aircraft functions safely as expected in its operating environment (SAE, 1996, 2010). The safety condition of the aircraft may be affected by improper concept and design, manufacturing, installation/integration and test, operation, and maintenance (SAE, 1996).

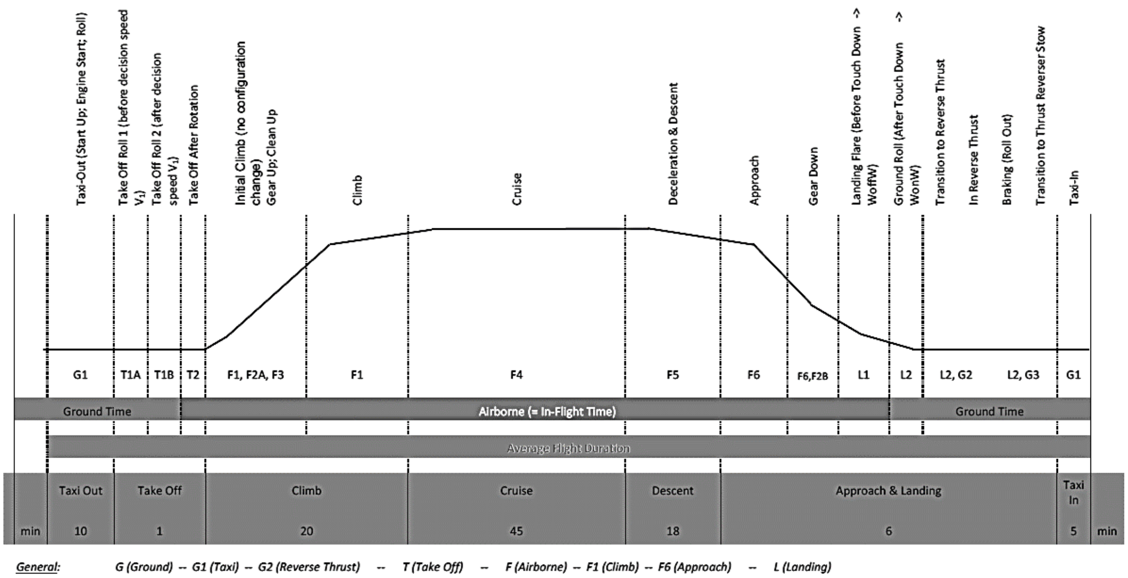


Fig. 80 Example average flight profile: airplane SAAB-EII 100 (Peterson, 2015, p. 21)

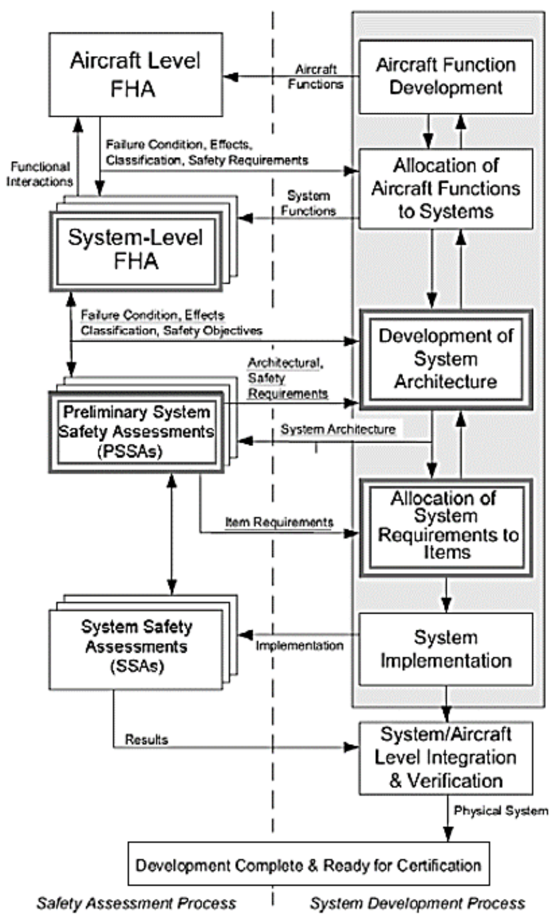


Fig. 81 ARP 4754A/ARP 4761 safety assessment process model (Valdivia de Matos et al., 2014)

Components from the natural environment are needed to quantify requirements. In general, customer requirements (i.e., marketing requirements & objectives), business case, and airworthiness in Fig. 76 may be initially defined using the characteristics in Table 41. The characteristics can be attributed to the whole civil airplane and flown down to each systems & subsystems (until the needed level) and their corresponding downstream activities in the life cycle of the aircraft. Attribution of the characteristics can be implemented using quality function deployment (QDF) (Eder, 2001). QFD follows the information flow implied in Table 46. QFD is systematic and traceable to track requirements from the top components in Fig. 76 until the whole aircraft, systems & subsystems, and corresponding downstream life cycle activities. Requirements shall express such characteristics in measurable quantities, e.g., using the quantities and units in defined in Appendix E (Section E.5). The basic building blocks of measurable quantities with major relationships are defined also in Appendix E (Section E.5). The basic building adopts the International System of Units (SI). NIST (2008) provides further details about each unit to define measurable quantities. Compound measurable quantities are obtained by combining the basic building blocks in the figure (Regtien, Van Der Heijden, Korsten, & Otthius, 2004). Measurable quantities enable measurement and inspection in aerospace (Saha, 2017, pp. 435-450). Qualification of measurable quantities may employ the basic building blocks of measurement and inspection methods in Appendix E (Section E.5). Specification of measurable quantities for requirements comes from understanding the natural environment especially the components in the subject of physics of flight. These components can be defined more specifically in the context of matter, energy and their relationships (Hirtz, Stone, McAdams, Szykman, & Wood, 2002, pp. 23-28) for the whole aircraft and its systems & subsystems. The components from the natural environment may affect people and the civil airplane. An initial guiding taxonomy of attributes from the natural environment to transform characteristics to measurable quantities in requirements is defined in Appendix E (Section E.5). The taxonomy has not been validated in the context of civil airplane design, but elements in the taxonomy shall be applicable to define measurable quantities in requirements for the whole civil airplane, its systems & subsystems, and corresponding downstream life cycle activities.

In conclusion, the civil airplane design is composed of different aspects. Aspects in civil airplane design are related to people (e.g., multidisciplinary team, pilot, passengers, crews, and maintainers), requirements, systems and subsystems, design & development process, and the natural environment (threats, physics and metrology).

6.3.1.2 Learning

This section addresses the questions related to learning defined in Table 44. Each question is answered in the remaining parts of this section.

6.3.1.2.1 Why to integrate learning in aircraft design?

Based on the opportunities given in the aviation industry and the needs of the Canadian aerospace industry to capitalize in such opportunities, integrating learning into aircraft design may lead to reach the expected outcome to maximize workplace entry-levels of students. Therefore, integration of learning into aircraft design will have a positive impact for the student, employer, Canadian aerospace industry, the government, and eventually society at large. In addition, integration may uncover research paths for future development.

6.3.1.2.2 What is learning?

Based on Section 6.2.3, this case study adopts the definition of learning suggested by EBD theory. EBD theory defines learning considering three factors: knowledge, skills, and affect (see Table 42).

6.3.1.2.3 What is to integrate learning in aircraft design?

Learning and aircraft design have been defined previously, but that is not the case for integration. In engineering, integration is defined as the process of combining software components, hardware components, or both into an overall system (ISO/IEC/IEEE, 2017). Since the concept is not applicable to this context, a more generic definition is adopted. The Oxford English Dictionary (OED) defines integration as the making up or composition of a whole by adding together or combining the separate parts or elements; combination into an integral whole: a making whole or entire. The definition implies two aspects 1) parts, and 2) whole; where parts make the whole. Parts in this case are learning and aircraft design. The two concepts shall make the whole learning in aircraft design.

In order to integrate learning in aircraft design, researchers and institutions have investigated and proposed workload (i.e., courses) for civil airplane design. For example, Castelli et al. (2010) reported the intention of integrating the CDIO[44] initiative to the new European Qualification Framework (EQF). The CDIO syllabus is composed of three elements: knowledge, skills, and attitudes (Crawley, Brodeur, & Soderholm, 2008). Using these elements, a high-level CDIO syllabus is formulated in Fig. 82. Since the formulated syllabus in the figure remains high-level, other researchers have attempted to be more specific. For example, Kamp (2011) presented what is known as the Delft aerospace engineering integrated curriculum. The integrated curriculum adopts the notion of knowledge, skills, and competence in the model in Fig. 83. The model defines foundational sciences, engineering sciences, aerospace engineering science, design and project skills, research skills, and intellectual skills (Kamp, 2011). Kamp's model seems to agree with the content and scope of civil aircraft design defined in Section 6.3.1.1.

1 TECHNICAL KNOWLEDGE AND REASONING
1.1 KNOWLEDGE OF UNDERLYING SCIENCE
1.2 CORE ENGINEERING FUNDAMENTAL KNOWLEDGE
1.3 ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES
2.1 ENGINEERING REASONING AND PROBLEM SOLVING
2.2 EXPERIMENTATION AND KNOWLEDGE DISCOVERY
2.3 SYSTEM THINKING
2.4 PERSONAL SKILLS AND ATTITUDES
2.5 PROFESSIONAL SKILLS AND ATTITUDES

3 INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION
3.1 MULTI-DISCIPLINARY TEAMWORK
3.2 COMMUNICATIONS
3.3 COMMUNICATIONS IN FOREIGN LANGUAGES

4 CONCEIVING, DESIGNING, IMPLEMENTING, AND OPERATING SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT
4.1 EXTERNAL AND SOCIETAL CONTEXT
4.2 ENTERPRISE AND BUSINESS CONTEXT
4.3 CONCEIVING AND ENGINEERING SYSTEMS
4.4 DESIGNING
4.5 IMPLEMENTING
4.6 OPERATING

Fig. 82 CDIO syllabus at the second level of detail (Castelli et al., 2010), originally from Crawley (2001)

[44] CDIO stands for conceiving, designing, implementing, and operating (CDIO, 2018). The latest version of the syllabus is CDIO syllabus v.2.0 (Crawley, Malmqvist, Lucas, & Brodeur, 2011).

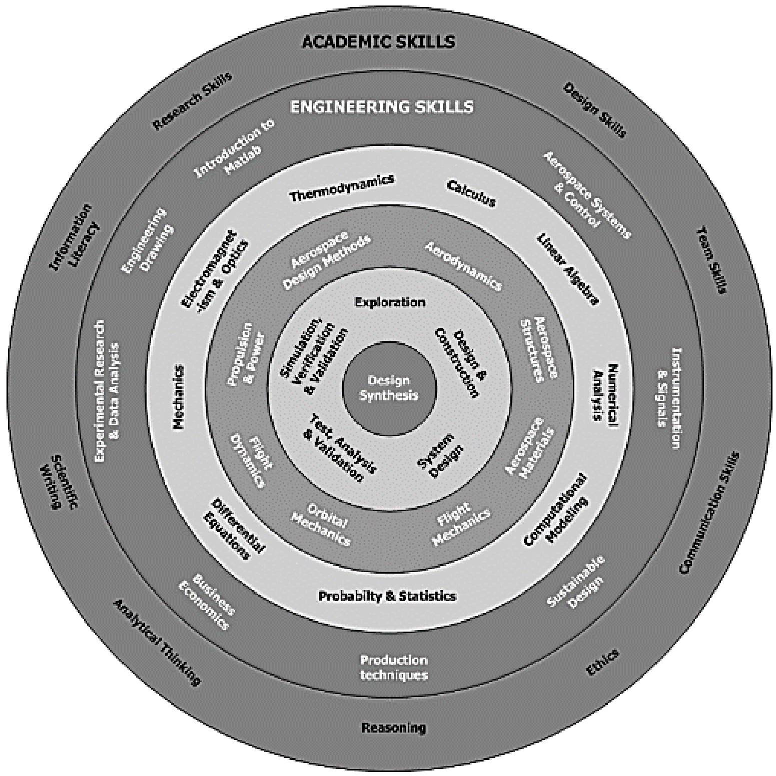


Fig. 83 The onion-shell model of the bachelor Aerospace Engineering at TU Delft (Kamp, 2011)

An alternative definition of the context of learning for civil airplane design has been published for the University of Tokyo (Rinoie, 2016). Fig. 84 defines an overview of courses and lectures at the department of aeronautics and astronautics in the university. According to the courses, learning progresses from basic engineering (i.e., mathematics, mechanics, electrical engineering, engineering measurements, computational engineering, applied dynamics, mechanical drawing, etc.) to aerospace engineering specific knowledge (i.e., aerodynamics, flight dynamics & control, structures & materials, propulsion, and design & system engineering). Students may even specialize in one aerospace engineering specific knowledge. Generally speaking, the workload (courses) in Fig. 83 and Fig. 84 seems to agree in the core technical knowledge of aerospace engineering. However, both figures may be complementing. In specific, Fig. 83 makes explicit important topics not explicit in Fig. 84 such as production techniques, sustainable design, business economics, ethics, scientific writing, etc. Therefore, Fig. 83 may help to complement Fig. 84.

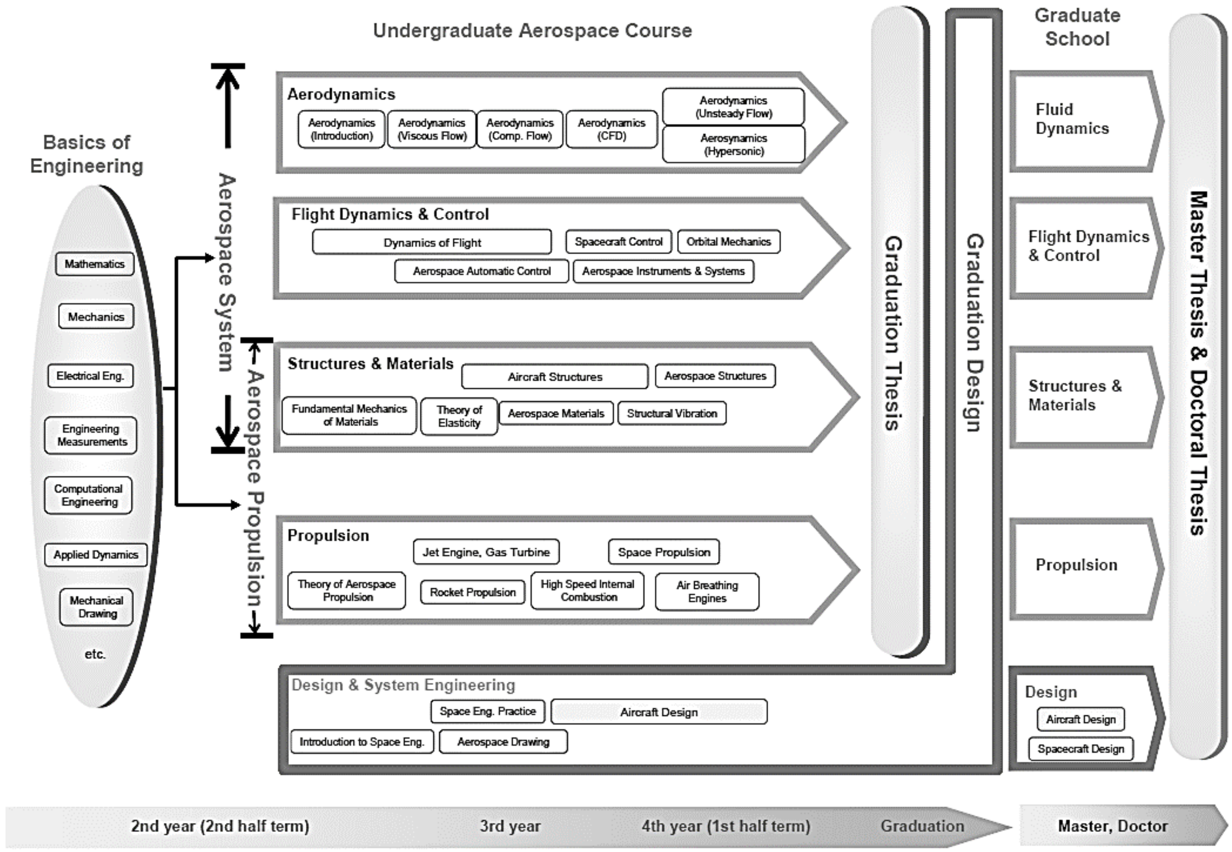


Fig. 84 Overview of courses & lectures at department of aeronautics & astronautics (Rinoie, 2016)

The US aerospace industries association (AIA), the US National Defense Industrial Association (NDIA), the US Employment and Training Administration (ETA), and industry leaders have worked together to develop a competency model for the aerospace industry (CareerOneStop, 2018). In the model, competency is defined as knowledge, skills, and abilities that affect a major part of one's job that correlates with performance on the job, that can be measured against well accepted standards, and that can be improved via training and development. The model is composed of 6 tiers: 1) personnel effectiveness competencies, 2) academic competencies, 3) workplace competencies, 4) industry-wide technical competences, 5) industry-sector technical competencies, and 6) others (management competencies and occupation-specific requirements). The tiers are illustrated in Fig. 85. Although the figure has a pyramid shape, it is not meant to be hierarchical or to imply that competencies at the top are at a higher level of skills. The model tackles more specific detail for tiers 1-4. Personnel effectiveness competencies (tier 1) are often referred as soft skills, learned in the home or community and reinforced at university and in the workplace. Academic competencies (tier 2) are critical competencies primarily learned in a university setting. Academic skills include cognitive functions and thinking styles likely to apply to all industries and occupations. Workplace competencies (tier 3) represent motives, traits, interpersonal, and self-management styles applicable to a large number of occupations and industries. Industry wide-technical competencies (tier 4) are specific to an industry or industry sector (i.e., aerospace). Industry wide-technical competencies represent the knowledge and skills that are common across sectors within the broader aerospace industry. These competencies build on but are more specific than competencies represented in lower tiers. Further details about each the competencies in each tier (i.e., tiers 1-4) are defined in Table 48. CareerOneStop (2018) specifies even more components for each category in the tiers in the table. Industry-wide competencies (tier 4) may correspond to core aerospace knowledge and skills in Fig. 83 and Fig. 84.

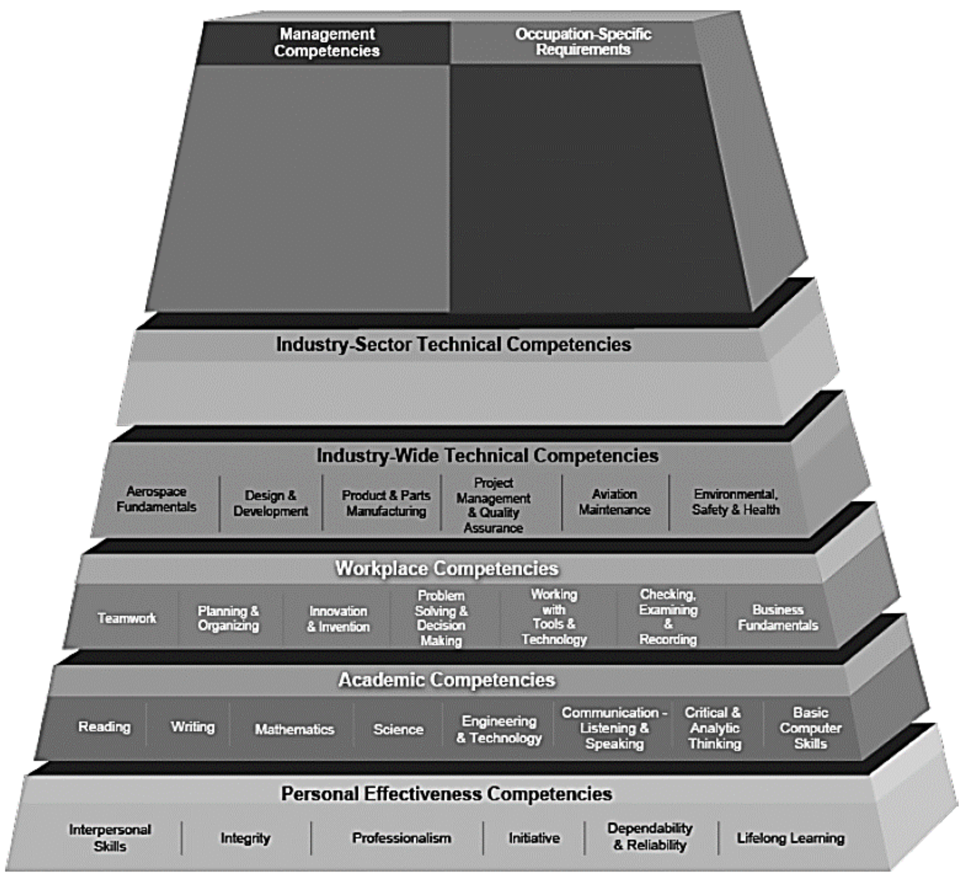


Fig. 85 Aerospace industry competency model (CareerOneStop, 2018)

Table 48 Tiers in aerospace industry competency model, extracted from CareerOneStop (2018)

Tier	Category	Description
Tier 1	Interpersonal skills	Displaying skills to work with others from diverse backgrounds.
	Integrity	Displaying accepted social and work behaviors.
	Professionalism	Maintaining a professional demeanor at work.
	Initiative	Demonstrating a willingness to work.
	Dependability & reliability	Displaying responsible behavior at work.
	Lifelong learning	Displaying a willingness to learn and apply new knowledge and skills.
Tier 2	Reading	Understanding written sentences and paragraphs in work-related documents.
	Writing	Using standard English to compile information and prepare written documents.
	Mathematics	Using principles of mathematics such as algebra, geometry, and trigonometry to solve problems.
	Science	Using scientific rules and methods to solve problems.
	Engineering & technology	Knowledge of the practical application of engineering science and technology including applying principles, techniques, procedures, and equipment to the design and production of various goods and services.
	Communicate-listening & speaking	Giving full attention to what others are saying and speaking in English well enough to be understood by others.
	Critical & analytical thinking	Using logic, reasoning, and analysis to address problems.
	Basic computer skills	Using a computer and related-application to input and retrieve information.
Tier 3	Teamwork	Working cooperatively with others to complete work assignments.
	Planning & organizing	Planning and prioritizing work to manage time effectively and accomplish assigned tasks.
	Innovation & invention	Formulating new ideas for and applications of processes and products.

	Problem solving & decision making	Applying knowledge of STEM[45] principles to solve problems by generating, evaluating, and implementing solutions.
	Working with tools and technology	Selecting, using, and maintaining tools and technology to facilitate work activity.
	Checking, examining & recording	Entering, transcribing, recording, storing, or maintaining information in written or electronic/magnetic format.
	Business fundamentals	Knowledge of basic business principles, trends, and economics.
Tier 4	Aerospace fundamentals	Knowledge of the aerospace industry and its principles, its key sectors, and relevant laws and regulations.
	Design and development	Application of engineering and mathematical principles to design aerospace components.
	Product & parts manufacturing	Assembly, installation, inspection, and repair of aerospace components.
	Project management & quality assurance	Management of projects to ensure products and processes meet quality system requirements as defined by the industry and customer specifications.
	Aviation maintenance	Inspection, servicing, and repair aircraft components and systems.
	Environmental, safety & health	Practices and procedures necessary to ensure a safe and healthy work environment.

At this point, the identified models agree about their description of learning in civil airplane design. The suggested models also agree with the scope of aircraft design defined in Section 6.3.1.1. In addition, the models of learning can be validated based on generic engineering design competency. The models agree with the structures of learning suggested in Fig. 86 and Fig. 87. Therefore, the models are complete and correct to represent integration of learning in civil airplane design.

[45] STEM stands for science, technology, engineering, and math.

Category	Subcategory	Sub-subcategory
Product	Constraints and specifications	
	Conceptual	
	Structural	
	Functional	
	Behavioral	
	Technical	
	Calculations	
Process	Manufacturing process	Installation requirements
		Realization
		Practical considerations
		Technology
	Design process	Realization
		Practical considerations
Contacts	Supplier	
	Customer	
	Competitor	
	Other stakeholders	
Environment	Legislation	
	Country/market	
	Environmental entity	
	Product lifecycle	

Fig. 86 Categories and subcategories of the dimension of engineering design (Saavedra, Villodres, & Lindemann, 2017)

Type	Description	Engineering – All disciplines	
General knowledge	To understand a phenomenon, a situation, a problem, a process, etc.	Mathematics	Linear algebra, Calculus, Differential Equations, Probability, Statistics, Numerical Methods, Partial Differential Equations, etc.
		Basic Sciences	Chemistry, Physics, Biology, Earth Science, etc.
		Engineering Sciences	Mechanics, Materials, Fluid Mechanics, Circuits, Thermodynamics, Heat Transfer, Mass Transfer, System Control, etc.
Specific knowledge in a professional environment	To know the technologies, the rules, the standards, the culture, etc.	Technologies, standards, regulations, safety, liability, intellectual property, ethic, role in the society	
Knowledge of procedures	To know the procedures, the methods, the processes, etc.	Product development process, engineering design process, engineering design tools (market research, functional analysis, QFD, design for cost and cost estimation, etc.)	
Operational skills	To know how to use methods, procedures, technologies, etc.	To have executed and practiced the design process	
Experiential skills	To know how to use tacit knowledge	Design by similarity, design by experience, etc.	
Social/ Personal skills	To know how to listen, to cooperate, to work in team, etc.	Teamwork, communications, leadership, negotiation, professionalism	
	Initiative, thorough, curious, etc.	Initiative, thorough, curious, practical, humble, responsible, adaptable, confident, awareness, respectable, entrepreneurialism	
	To manage life (personal and professional), To feel (intuition, perception, etc.)	Self-awareness, managing emotions, motivating oneself, empathy and handling relationships	
Cognitive skills	To solve problem, to design, to manage a project, to take decisions, etc.	To know your limitations, to create, to look at the big picture, to manage projects (including the system engineering perspective), to decide (decision-making), to learn how to learn, to manage information and knowledge, to define a problem, to define potential solutions, to learn from past experiences, to manage resources, to take and manage risk	

Fig. 87 Proposed definition of the design engineering competency (Angeles et al., 2004)

6.3.1.2.4 Who integrates learning in aircraft design?

Based on the information in Section, there are several stakeholders in integrating learning in aircraft design. These stakeholders are students, professors, curriculum developers at universities, the government through specific institutions, international educators, and industry partners. All these stakeholders work together to integrate learning in aircraft design.

6.3.1.2.5 Where to integrate learning in aircraft design?

Learning in aircraft design can be integrated through different venues. Learning can be integrated at course level. For example, each element in the shell-model in Fig. 83 is a course. This is also the case in Fig. 84. Learning in aircraft design can be integrated at the complete curriculum level. For example, such efforts is defined in Fig. 83 and Fig. 84. Both figures try to depict the whole scope of learning in aircraft design. Learning in aircraft design can also be integrated through conferences, forums, workshops/seminars, industry-university collaborations, short term lectures, and publications (e.g., journal articles and books).

6.3.1.2.6 When to integrate learning in aircraft design?

In order to ingrate learning effectively in aircraft design, a life cycle perspective shall be considered. This life cycle perspective is executed step by step by the used of design methodologies. Thus, design methodologies help to break down the whole civil airplane design into more simple tasks that can be learnt, communicated, and distributed to teams more easily. More details about design methodologies are presented in Section 6.3.1.3 and 6.3.1.4.

6.3.1.2.7 How to integrate learning in aircraft design?

The models of learning in civil airplane design are useful tools to align intended learning outcomes with the mission of learning. Depending on the mission, learning outcomes may be associated to specific courses or to the curriculum at large (Heywood, 2005b; Ostafichuk, 2012). For example, Fig. 88 defines that learning comes from the mission of an academic program. The mission in this case is to have an effective and efficient civil airplane design. Therefore, intended learning outcomes shall lead to the mission: to have an effective and efficient civil airplane design. This learning outcomes can be attributes to specific teaching and learning activities and their respective assessment. Assessment qualifies the effectiveness and efficiency of learning. A sample of generic assessment methods are defined in Fig. 90. Connection between intended learning outcomes, teaching and learning, and assessment are illustrated in Fig. 89. If Fig. 88 and Fig. 89 are integrated, the learning process starts from the mission of the instruction finalizing with assessment. Design methodologies may facilitate to allocate logically the intended learning outcomes and assessment along the design process.

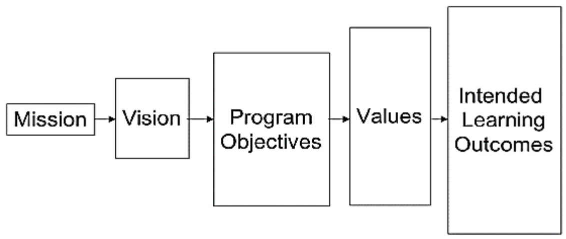


Fig. 88 Alignment of intended learning outcomes with mission (Crawley et al., 2011)

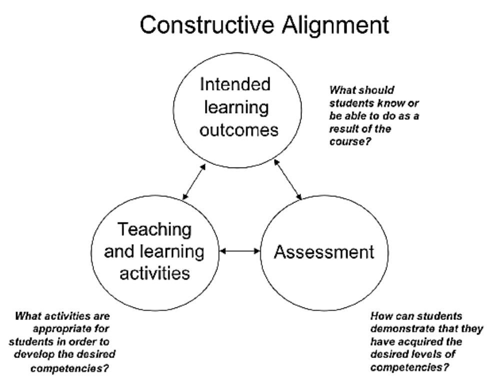


Fig. 89 Alignment of intended learning outcomes with teaching and assessment (Crawley et al., 2011)

	Written/ Oral Questions	Performance ratings	Product reviews	Journals/ portfolios	Self-report instruments
Conceptual understanding	X				
Problem solving and procedural knowledge	X			X	
Knowledge creation and synthesis		X	X	X	
Skills and processes		X	X	X	X
Attitudes			X	X	X

Fig. 90 Assessment methods (Crawley, Niewoehner, & Koster, 2010)

Any change or creation of learning instructions shall be also compared in monetary and performance terms (i.e., efficiency and effectiveness) to a baseline. Existing learning instructions may set the baseline to evaluate improvements of changes or creations of learning instruction. In monetary terms, suggestions from the model in Fig. 91 can be followed. The model shall be applied for the existing and proposed learning instruction to compare their relative utility. In contrast to utility, learning performance can be measured following the experimental strategy in Fig. 92. The strategy serves three purposes: 1) indicating how well reforms are working and reveal areas for future adjustments, 2) convincing an organization or learner about the instruction effectiveness, and 3) providing evidence to learners to explain the rational to do certain things and their benefits (National Research Council, 2015). The strategy suggests breaking down the population of learners during time into four cohorts. The cohorts of students are exposed to different learning approaches with the same expected learning outcomes. The first cohort refers to learners doing a pre-test (e.g., diagnostic assessment) followed by an experimental treatment in the instructional method and one post-test assessment. The second cohort excludes a pre-test, but students are exposed to an experimental treatment and a post-test assessment. The third cohort includes learners conducting a pre-test followed by no intentional changes in the instruction and a post-test assessment. The fourth cohort refers to the scenario where learners are exposed to the regular instructional method and only one-post-test assessment is conducted. The four cohorts implicitly have used the suggestions in EBD theory especially considering the models in Fig. 67 and Fig. 68. The combination of all these models can help to provide experimental validity to the suggested theoretical guidance in monetary and performance terms.

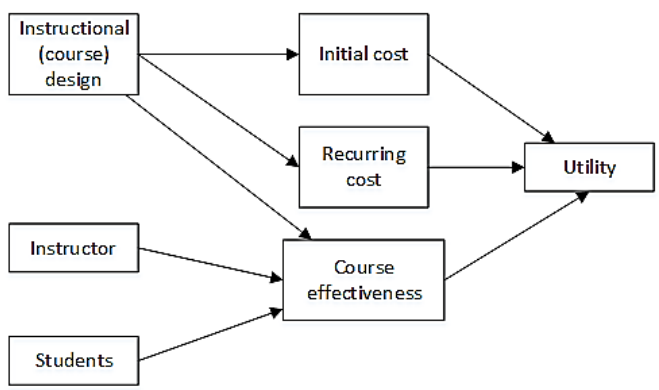


Fig. 91 Relationships between the elements of course design (Herrmann, 2016)

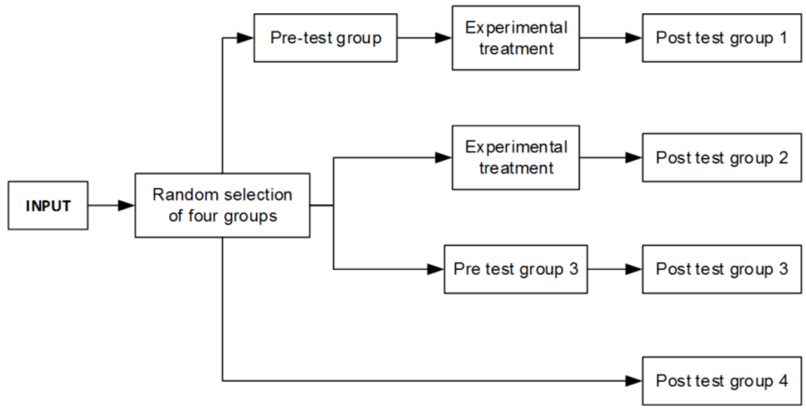


Fig. 92 A research strategy for dealing with small groups (Heywood, 2005a, p. 399)

6.3.1.3 Design methodologies

6.3.1.3.1 What is a methodology?

In general, the Oxford English Dictionary defines a methodology as the branch of knowledge that deals with method generally or with the methods of a particular discipline or field of study. Considering that methodologies relate to domain of study, the definition shall be understood from engineering perspective. In engineering, a methodology is a system of practices, techniques, procedures, and rules used by those who work in a discipline (ISO/IEC/IEEE, 2017). This discipline can be civil aircraft design.

6.3.1.3.2 What is a design methodology?

A design methodology is a systematic approach to create a design consisting of the ordered application of a specific collection of tools, techniques and guidelines (ISO/IEC/IEEE, 2017).

Design methodologies adopt the design process and life cycle perspective as the guiding framework to become a systematic approach to create design consisting of the ordered application of a specific collection of tools, techniques, and guidelines. The framework also enables to define and evaluate systematically learning which can eventually lead to improve design performance.

Design methodologies have been employed in different engineering design contexts. For example, Platanitis, Pop-Iliev, and Nokleby (2009) use the design process to evaluate capstone design courses in mechanical systems design and advanced mechatronics. Based on the authors, the design process can be accompanied by deliverables and reports. Elements in the process, deliverables and reports can be marked using rubrics, e.g., refer to Fig. 93. Predefined marks can be assigned to the rubrics for each element, deliverables and reports. For example, Fig. 93 illustrates a sample two-dimensional rubric for the element #A09 in Fig. 93 showing levels of knowledge application and learning levels along with assigned grades and descriptors for each level (y-axis) and rank (x-axis) for advanced mechatronics. These rubrics provide guidance to undergraduate and graduate students in how to address the design requirements for maximum marks. Rubrics also assist instructors with clearly defining the design requirements. Woodhall and Strong (2009) also apply rubrics along the design process for courses related to fundamentals of design engineering and multidisciplinary design projects. For example, Fig. 95 is a key concepts rubric to be expected for the problem definition phase of the design process. Fig. 96 is a steps rubric expected for the problem definition phase of the design process. Both Platanitis et al. (2009) and Woodhall and Strong (2009) provide applications using design methodologies to evaluate learning in design. Their examples are limited to specific phases of the design process; thus, rubrics shall be established along the whole design process or life cycle perspective of design and development.

SUMMARY OF MARKING RUBRICS FOR ENGR4320U Advanced Mechatronics Group Design Projects (Winter 2009)			
(A) Engineering Design Process		(B) Engineering Reports	
#	Element	#	Element
A01	Requirements	B01	Logbook
A02	Background Search	B02	Report Write-Up
A03	Design Plan/Project Management	B03	Assembly and Sub-Assembly Drawings
A04	Brainstorming	B04	Bill of Materials
A05	Sketching Ideas	B05	Detail Design Drawings
A06	Engineering Specifications (Benchmarking)	B06	Tolearances
A07	Functional Decomposition	B07	3D Renderings of Final Design
A08	Concept Development and Screening/Selection	B08	CAD Package Proficiency
A09	Form Design and Engineering Analysis	B09	Circuit Drawings
A10	FEM Package Proficiency	B10	Presentation
A11	Motion Simulation Package Proficiency		
A12	Design for Manufacturing		
A13	Design for Safety		
A14	Control Algorithm		
A15	Test Plan, Test Results, and Product Validation		

Fig. 93 Summary of marking rubrics for the course ENGR4320U – Advanced mechatronics (Platanitis et al., 2009)

Element #A09			RANKS					
			IDEAS		CONNECTIONS		EXTENSIONS	
FORM DESIGN AND ENGINEERING ANALYSIS	LEVELS	BASIC	D 50-59% 1.0	- defines form of components - determines materials and dimensions	B- 70-72% 2.7	- performs informed and justified material selection	A- 80-84% 3.7	- optimizes design based on engineering analysis - strives to integrate multiple components into a multifunctional one
		INTERME-DIATE	C 60-66% 2.0	- defines type and form of interfaces (where function happens)	B 73-76% 3.0	- determines component dimensions based on chosen materials, the loading and other constraints for achieving a given minimum safety coefficient	A 85-89% 4.0	- uses DFM and DFA methods to improve design - verifies calculations through various means including use of FEA and motion simulation
		ADVANCED	C+ 67-69% 2.3	- incorporates engineering analysis into the design process to verify "what if" scenarios	B+ 77-79% 3.3	- performs and clearly documents all necessary engineering calculations based on theoretical formulas	A+ 90-100% 4.3	- skillfully uses FEM as a quick tool for design form improvement - demonstrates developed skills and judgment to determine if the obtained FEM results make sense

Fig. 94 Sample two-dimensional rubric showing levels of knowledge application (ranks) and learning (levels) along with assigned grades and descriptors for each level and rank coordinate for advanced mechatronics (Platanitis et al., 2009)

Key Concepts	Ideas	Connections	Extensions
research doesn't limit options or scope	research covers basics of problem and potential solutions	research sources stretch beyond web based searching	research materials include interviews, surveys, review of existing solutions, search into patents, regulations, standards
	library resources are utilized, sources are academic/ credible	there exists significant questioning and challenging of information	research does not exclude any potential solutions but remains open ended
uses appropriate tools	uses tools such as objective trees, sketches, etc	is able to convert outputs into tangible criterion for design	strengths/ weaknesses of different tools are highlighted, others are used to compliment/ correct for those strengths/ weaknesses
			sketches, objectives, etc. are iterated as the project moves
recognizes differences between functional requirements and limitations	requirements and constraints are clearly delineated and articulated	client suggested requirements/ constraints are separated from user defined requirements/ constraints	is able to iterate requirements over time if they change, and able to introduce new limitations as they arise
acknowledges team/ interpersonal hurdles, uses appropriate	recognizes team strengths, potential weaknesses is knowledge	addresses concerns or disagreements early	work is fairly distributed, allowing for learning and growth by each team member as well as utilizing their strengths

Fig. 95 Key concepts rubric for the problem definition phase of the design process (Woodhall & Strong, 2009)

Key Steps	Ideas	Connections	Extensions
forming the problem statement	statement is open ended	statement is multidimensional in nature; showing constraints and potential strengths	statement shows awareness of human factors, resource constraints, and client need
	statement accurately reflects project needs		statement is aware of potential biases from client needs, terminology
identifying functional requirements	takes client need and converts it into necessary product performance needs	is able to separate needs from wants	able to show potential strengths/weaknesses in relating different functional requirements
	identifies the WHO as well as the WHAT of the problem	is able to determine what the end user needs (if not necessarily the client)	is able to qualify which are most important to project success, which are the greatest hurdles
recognizing constraints and limitations	understands given constraints from client	is able to articulate other constraints/limitations not directly specified by client	is able to differentiate between true limitations and unnecessary or overcomeable hurdles
	foresees operational concerns/pitfalls	is able to see constraints/limitations for the life cycle of the project	is able to overcome limitations or turn them into strengths
defining a schedule and forming a team	group memos and progress reports are submitted on time and with appropriate formatting	memos show insight into group operations, progress reports adequately show project progress to date and future goals	memos and progress reports form a clear timeline of project completion and group development
	Gantt chart is clear, follows acceptable timelines, adequately explains project 'flow'	work is fairly distributed, providing opportunities for all members to actively contribute	Gantt chart is revised as project progresses
	team prepares a working agreement and abides by it for duration of project		team dynamics issues are addressed and overcome

Fig. 96 Key steps rubric for the problem definition phase of the design process (Woodhall & Strong, 2009)

Both Platanitis et al. (2009) and Woodhall and Strong (2009) employ the ICE approach of assessment to measure the degree to which students are moving through different stages of learning, from novice to expert. ICE stands for ideas, connections, and extensions (Woodhall & Strong, 2009). The ideas stage represents the basic elements of learning; with students being assessed on their understanding of the basic steps in a process, the essential vocabulary, and a rudimentary understanding of the skills set required within the appropriate phase. After ideas, a student progresses to the connection stage. This stage occurs when students demonstrate they understand relationships between the different stand-alone elements in the ideas stage. The extensions stage is the last level of mastery. Extensions stage happens when students internalize the material and are able to develop new learning on their own.

	Poor	Acceptable	Good	Excellent
1. Problem Definition	▪ Unclear. ▪ Does not describe the practical applications and importance of the problem. ▪ Does not provide any evidence or understanding of current literature. ▪ Is not technically relevant. ▪ Does not integrate principles from all courses involved. ▪ Does not address any contemporary societal issues.	▪ Clear. ▪ Describes the practical applications and importance of the problem. ▪ Refers to current literature (3+ references). ▪ Somewhat technically relevant. ▪ Somewhat interesting. ▪ Integrates principles from all courses involved. ▪ Addresses contemporary societal issues.	▪ Clear. ▪ Describes the practical applications and importance of the problem. ▪ Refers to and demonstrates understanding of current literature (3+ references). ▪ Technically relevant. ▪ Interesting. ▪ Integrates principles from all courses involved. ▪ Addresses contemporary global / societal issues.	▪ Very clear. ▪ Describes the practical applications and importance of the problem. ▪ Refers to and demonstrates understanding of current literature (5+ references). ▪ Technically relevant. ▪ Very interesting and new. ▪ Integrates principles from all courses involved. ▪ Addresses important contemporary global / societal issues.
2. Project Objectives	▪ No objectives. ▪ Unclear objectives ▪ Not written in technical terms ▪ Not addressing each and every area (aero, structures, flight mechanics, etc.) integrated in the project.	▪ Written in technical terms. ▪ Address each and every area (aero, structures, flight mechanics, etc.) to be integrated in the project.	▪ Clear. ▪ Written in technical terms. ▪ Address each and every area (aero, structures, flight mechanics, etc.) to be integrated in the project.	▪ Very clear. ▪ Written in concise, technical terms. ▪ Address each and every area (aero, structures, flight mechanics, etc.) to be integrated in the project.
3. Multidisciplinary Analysis	▪ No assumptions listed. ▪ Incorrect modeling. ▪ Superficial or incorrect analysis in one or more areas. ▪ No use of modern tools.	▪ Some assumptions listed. ▪ Correct modeling. ▪ Correct analysis in each area. ▪ Use of modern tools in some areas.	▪ Appropriate assumptions listed. ▪ Correct modeling. ▪ In-depth analysis in each area. ▪ Use of modern tools in some areas.	▪ All appropriate assumptions listed. ▪ Correct modeling. ▪ In-depth analysis in each area. ▪ Use of modern tools in all areas.
4. Results	▪ Poor quality graphs and tables. ▪ Numbers and trends do not make sense. ▪ Results do not agree with published data.	▪ Graphs and tables are prepared following standard guidelines. ▪ Some of the results make sense ▪ Some agree with published data.	▪ Good quality graphs and tables. ▪ Numbers and trends make sense. ▪ Results agree well with published data.	▪ Excellent quality graphs and tables in all areas. ▪ Numbers and trends make sense in all areas. ▪ Results agree very well with published data.
5. Discussion	No understanding of the results is evident in one or more subjects.	Some understanding of the results is evident in most subjects.	A good understanding of the results is evident in most subjects.	An excellent understanding of the results is evident in all subjects.
6. Evaluation and Reflection	▪ Superficial or no evaluation of the results. ▪ No reflection on the assumptions made to model the problem. ▪ No understanding of the impact of the solution in a practical, global / societal context is evident.	▪ Some evaluation of the results. ▪ Some comments on the assumptions made to model the problem. ▪ Some understanding of the impact of the solution in a practical, global / societal context.	▪ Good evaluation of the results. ▪ Reflection on the assumptions made to model the problem. ▪ Good understanding of the impact of the solution in a practical, global / societal context.	▪ Excellent evaluation of the results. ▪ Appropriate reflection on the assumptions made to model the problem. ▪ Excellent understanding of the impact of the solution in a practical, global / societal context.

Fig. 97 Rubric used to evaluate project reports (Mourtos, Papadopoulos, & Agrawal, 2006)

Mourtos et al. (2006) used design methodologies to define a flexible, problem-based, integrated aerospace engineering curriculum. They used a problem-solving methodology to represent the design process. The 6 steps methodology consists of problem definition, project objectives, multidisciplinary analysis, results, discussion, and evaluation and reflection. To assess the effectiveness and efficiency of learning, the authors used a rubric along the adopted methodology. The sample rubric is defined in Fig. 97.

Based on the work of the previous authors, it is evident that design methodologies are an effective framework to integrate effective and efficient learning in civil aircraft design. The presented ideas in this section are generic; so, they need to be tailored to specific missions, desired learning outcomes, and assessment.

6.3.1.4 Integrating learning through design methodologies in aircraft design

This section addresses the question: how to integrate learning through design methodologies in aircraft design. Based on Section 6.2.3, this case study adopts the definition of learning suggested by EBD theory. EBD theory defines learning considering three factors: knowledge, skills, and affect (see Table 42). In particular, learning is modeled through workload (refer to Fig. 67 and Fig. 68). Workload is aircraft design which refers to the design process and the results (systems and subsystems) of the design process. Specifying workload as civil airplane design is the input to subsequently define knowledge, skills, and affects needed to quantify mental stress. Such quantification is useful to manage (plan, distribute, execute, and control) workload in civil airplane design projects. Systems engineering as a design methodology is adopted to manage workload based on the foundation of learning in EBD theory.

System engineering have been taught for civil airplane design. For example, Moir and Seabridge (2013) employ system engineering considering aspects such as aircraft systems, design and development process, design drivers (e.g., business environment, project environment, product environment, operating environment, sub-system environment, and obsolescence), system architectures, system integration, verification of system requirements in the life cycle, configuration control, power systems issues, and other practical considerations (e.g., key characteristics of aircraft systems, aircraft systems examples, and managerial issues). Although Moir and Seabridge (2013)'s work is very informative, it missed an integrative step-by-step guidance (i.e., a design methodology). Another author employing design methodologies in aircraft design is Gudmundsson (2014). Gudmundsson (2014) also introduces methods and procedures for general aviation aircraft design. The methods and procedures include aspects such as aircraft design process, aircraft cost analysis, initial sizing, aircraft conceptual layout, aircraft structural layout, aircraft weight analysis, selecting the power plant, the anatomy of the airfoil, the anatomy of the wing, the anatomy of lift enhancement, the anatomy of the tail, the anatomy of the fuselage, the anatomy of the landing gear, the anatomy of the propeller, aircraft drag analysis, and performance (i.e., take-off, climb, cruise, range analysis, descent, and landing) and miscellaneous notes. Although Gudmundsson (2014) is comprehensive, the work can be complemented with important aspects related to industry knowledge, and life cycle considerations. In addition to Gudmundsson (2014), Sadraey (2013) also adopts systems engineering for airplane design. Sadraey (2013) considers aspects such as aircraft design fundamentals, systems engineering approach, aircraft conceptual design, preliminary design, wing design, tail design, fuselage design, propulsion system design, landing gear design, weight of components, aircraft weight distribution, and design of control surfaces. Although this work missed aspects and details suggested by Moir and Seabridge (2013) and Gudmundsson (2014), Sadraey (2013, pp. 45-46) presents the idea of 47 aircraft design steps that integrates activities for civil airplane design. In more recent work, Sadraey and Bertozzi (2015) propose 50 steps for civil aircraft design. The steps are listed in Fig. 98. Each step shall be associated to specific deliverables and reports that comes from the intended learning outcomes.

Assessment of student learning happens through design reviews in the design process for civil airplane design. A high-level abstraction of the design process is presented in Fig. 99. The figure defines three phases in the design process: conceptual design, preliminary design and detail design. The figure shows that the phases in design process are iterative and related, but the 50 steps progress through them from general to more specific details. Four design reviews during the design process can be conceptual design review (CDR), preliminary design review (PDR), evaluation and test review (ETR), and critical (final) design review (FDR) (Sadraey & Bertozzi, 2015). Design reviews can be integrated to the design process as illustrated in Fig. 100. Single or cumulative deliverables and reports can be associated to each design review. Deliverables and reports shall consider the three learning factors in EBD theory: knowledge, skills, and affect. Based on Fig. 88, deliverables and reports shall be originated from the mission. The mission shall align with real civil airplane requirements. This alignment can be obtained following the model in Fig. 76, relevant material from aircraft design (i.e., Section 6.3.1.1), new civil aircraft developments (see Fig. 168), and existing civil aircraft (General Aviation Manufacturers Association, 2016).

1. Derive aircraft design technical requirements, objectives and specifications from the customer order and problem statement
2. Design program and management planning (e.g., Gantt chart and checklists)
3. Feasibility studies
4. Risk analysis
5. Functional analysis and allocation
6. Design team allocation
7. Aircraft Configuration design
8. First estimation of aircraft maximum take-off weight
9. Estimation of aircraft zero-lift drag coefficient
10. Calculation of wing reference area
11. Calculation of engine thrust or engine power
12. Wing design
13. Fuselage design
14. Horizontal tail design
15. Vertical tail design
16. Landing gear design
17. Propeller design or selection (if prop driven engine)/inlet design (if jet engine)
18. First estimate of weight of aircraft components
19. Second estimate of aircraft maximum take-off weight
20. First calculation of aircraft center of gravity limits
21. Relocation of components to satisfy stability and controllability requirements
22. Redesign of horizontal tail and vertical tail design
23. Design of control surfaces
24. Control system design
25. Calculation of aircraft C_{D_o}
26. Re-selection of engine
27. Calculation of interferences between aircraft components
28. Incorporation of design changes
29. First modifications of aircraft components
30. First calculation of aircraft performance
31. Second modification of aircraft to satisfy performance requirements
32. First stability and control analysis
33. Third aircraft modification to satisfy stability and control requirements
34. Manufacturing of aircraft model
35. Wind tunnel test
36. Fourth aircraft modification to include aerodynamic considerations
37. Aircraft structural design
38. Calculation of weight of aircraft components
39. Second calculation of aircraft center of gravity limits
40. Fifth aircraft modification to include weight and cg considerations
41. Second performance, stability and control analysis and design review
42. Sixth aircraft modification
43. Aircraft systems design (e.g., electric, mechanical, hydraulic, pressure, and power transmission)
44. Manufacturing of the aircraft prototype
45. Flight test
46. Seventh aircraft Modification to include flight test results
47. Trade-off studies
48. Optimization
49. Certification, validation or customer approval tests
50. Eighth Modification to satisfy certification requirements

Fig. 98 Major design steps in an airplane design process (Sadraey & Bertozzi, 2015)

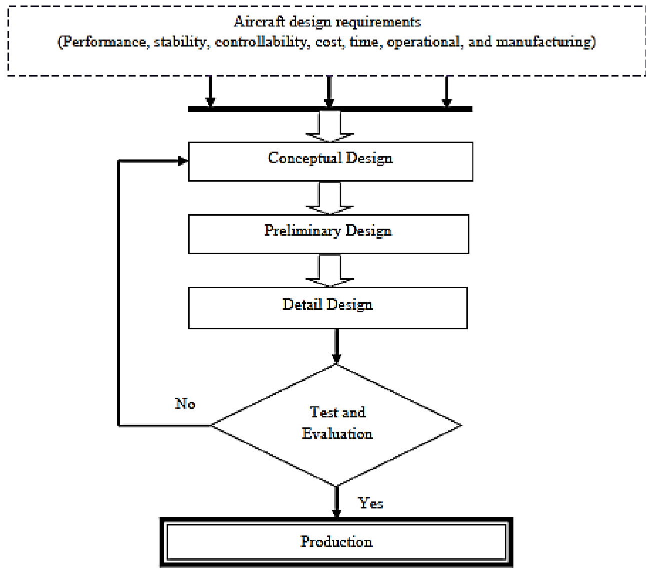


Fig. 99 Design process (Sadraey & Bertozzi, 2015)

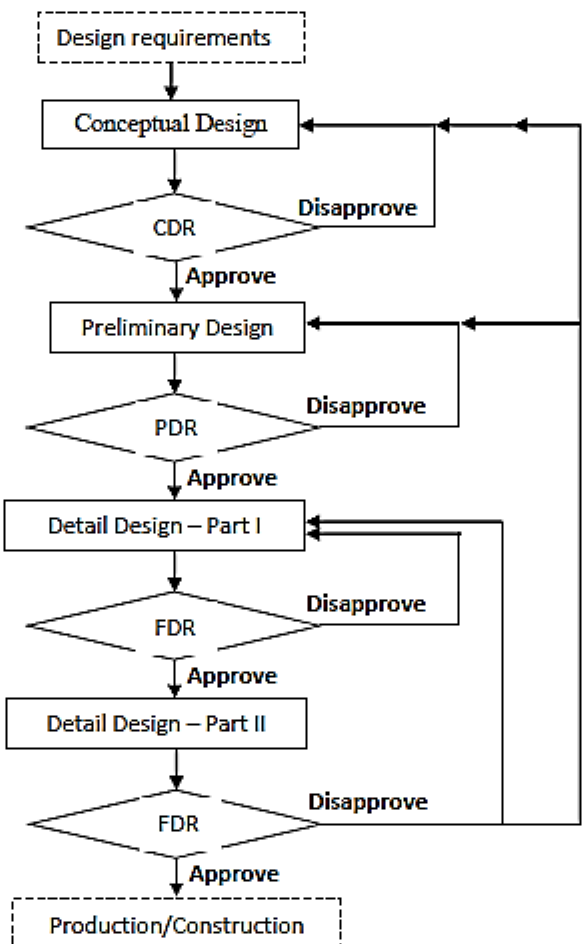


Fig. 100 Design reviews in the design process (Sadraey & Bertozzi, 2015)

Revolutionary changes in learning civil aircraft design can be investigated based on stress management as suggested in EBD theory (Section 6.2.5). Stress management may lead to redistribute the design process (i.e., changes in workload). This redistribution shall respect the mission of the intended learning outcome, but it may suggest the right chunks of competence to perform at the optimal stress level. These right chunks may lead to create or redefine learning courses or complete aerospace engineering, for example by reengineering the content in Fig. 84. Stress management may also complement the traditional assessment methods in the form of design reviews, rubrics, and others in Fig. 90 by introducing more objective physiological aspects from human factor. Stress management can also lead to create new or modify existing methods & tools needed to execute the steps in civil airplane design. At this point, the process can be implemented by methods and tools suggested by Moir and Seabridge (2013), Gudmundsson (2014), and Sadraey (2013).

To sum up, integration of learning in civil airplane design is considered complete at this point. Future development shall follow the previous discussions in this section. In addition, integration of learning can be further investigated writing detail procedures for each step. Detail procedures can be aligned with the mission and intended learning outcomes. The mission and intended learning outcomes can be manifested in more detail description of expected representations of either the entire civil airplane (Fig. 65), systems & subsystems (Fig. 70) or their integration (Fig. 77, Fig. 81 or Table 46).

6.3.2 Conflict identification

Conflict identification briefly evaluates the content presented for aircraft design in Section 6.3.1.1 and the proposed integrated learning (i.e., 50 steps and assessment) in Section 6.3.1.4. Conflict identification is summarized in Table 49. Conflict identification is based on the root concepts of EBD theory: human environment, built environment, natural environment, design process, and life cycle.

Table 49 Conflict identification

C#	EBD root concept	50 steps	Assessment
C1	Human environment	Missing suppliers.	Missing specific assessment of knowledge, skills, and affect.
C2	Built environment	Weak inclusion of specific aspects related to standards, laws & regulation.	Missing specific deliverables and reports from intended learning outcomes.
C3	Natural environment	Weak inclusion of specific aspects related to environmental impacts and safety.	Missing specific deliverables and reports from intended learning outcomes.
C4	Design process	To be aligned with real design process.	Missing integration of assessment between real design process, deliverables, reports, and learning outcomes.
C5	Life cycle	To be better integrated to manufacturing, installation/ integration & test, operation, maintenance, and disposal.	Missing specific assessment of deliverables and reports for manufacturing, installation/integration & test, operation, maintenance, and disposal.

Based on the identified conflicts in Table 49, solution generations are needed to provide direction to close the gaps. Solution generation is presented in Section 6.3.3.

6.3.3 Solution generation

This section provides guidance to address the identified conflicts in Table 49. Table 50 defines general solutions for each identified conflict in Table 49. It is important to point out that the generated solutions shall be applied to each of the 50 steps in Fig. 98. The identified conflicts may be related to each other. To find the right sequence to solve them, a life cycle perspective shall be used.

Table 50 Solution generation

S#	EBD root concept	50 steps	Assessment
S1	Human environment	Make explicit the role of suppliers.	Define specific assessment of knowledge, skills, and affect.
S2	Built environment	Strengthen specific aspects related to standards, laws & regulation.	Define specific deliverables and reports from intended learning outcomes.
S3	Natural environment	Strengthen specific aspects related to environmental impacts and safety.	Define specific deliverables and reports from intended learning outcomes.
S4	Design process	Investigate real design process.	Define integration of assessment between real design process, deliverables, reports, and learning outcomes.
S5	Life cycle	Investigate and improve integration to manufacturing, installation/ integration and test, operation, maintenance, and disposal.	Define specific assessment of deliverables and reports for manufacturing, installation/integration and test, operation, maintenance, and disposal.

The proposed solution in Table 50 are generic for educational purposes in this case study. Effort to create more specific real solutions shall consider the needs of new civil aircraft developments. Such developments are identified in Fig. 168. Each development in reality is a unique endeavour.

6.4 Data analysis

Data analysis in this section follows the same method as presented in Chapter 5. The rest of the section is elaborated based on each root concept in EBD theory (Section 5.4.1.1 to 5.4.1.5). Each root concept in EBD theory is complemented with the respective concepts in the proposed core ontology. Section 6.4.1.6 ends with a discussion about the findings in data analysis.

6.4.1.1 Natural environment

The natural environment refers to all the [natural] laws in a product's working environment (Zeng, 2004a, 2015). Concepts in the proposed core ontology related to the natural environment are summarized in Table 35.

Table 51 Natural environment and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Natural environment	Environment	Environmental impacts (emissions, noise), pressurization, hypoxia, oxygen, altitude, climate / meteorology (pressure, density, temperature, moisture, wind, and icing), chemical/electrochemical attacks, corrosion, bird strikes, physics of flight, vision problems in night flight (human limitations), etc.
	Interaction	Functional interactions (Fig. 81), complex interaction of various disciplines in civil airplane design, etc.
	Risk	Risk (e.g., financial burden), complexities in commercial aircraft development
	Safety	Safety, ARP 4754A/ARP 4761 safety assessment process model, airworthiness, safe and healthy work environment, etc.
	State	The whole aircraft functions safely as expected in its operating environment (i.e., state of aircraft in function), state of information, state associated with feeling
	Validation	Business case, business needs, customer profiles, marketing, feasibility, economics, type certificate, etc.
	Verification	Metrology, quantity and units [SI], inspection methods, certification tests, flight test, reviews, etc.

6.4.1.2 Built environment

The built environments are the artefacts designed and created by human beings (e.g., man-made devices) (Zeng, 2004a, 2015). Concepts in the proposed core ontology related to the built environment are summarized in Table 36.

Table 52 Built environment and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Built environment	Architecture	Aircraft morphology, configuration, function, integration, systems architecture, tier structure of the Canadian aerospace industry, aircraft system hierarchy, etc.
	Attribute	Attributes, taxonomy of attributes, etc.
	Availability	Availability, availability of cognitive resources
	Baseline	Future aircrafts, competitive landscape (Fig. 174), baseline to evaluate improvements of changes or creations of learning instruction
	Concept of operations	Business case, design space / technology insertion (Fig. 174), aircraft delivery, future aircraft, costs, entry into service timeline, global aviation, etc.
	Concern	Airworthiness, TRL, certification, relevant laws and regulations, competency, aviation industry, economical investment, competitiveness, profitability, value-driven design, etc.
	Document	Type certificate, drawings, requirements, WBS, schedules, engineering bill of materials, manufacturing bill of materials, production site locations and layouts, life cycle costing, etc.
	Enabling system	Routes worldwide, universities, IATA, supply chain, aerospace clusters, manufacturing, maintenance, facilities, personnel, security, airports (Fig. 175), etc.
	Flexibility	Flexibility [of product, of service]
	Functional requirement	Maximize workplace entry-level skills of Canadian aerospace candidates, aircraft functions safely, major function, lesser function, function deployment, specific function, function [of system], etc.
	Interface	Integration [shared boundary to connect separated part-part, part-whole]

	Issue	Power system issues, managerial issues
	Need	Business needs, need for competitiveness, needs of the Canadian aerospace industry, needs of new civil aircraft developments, etc.
	Operational concept	Flight profile, aircraft operation and mission profile
	Port	Kick-off meeting [flow of information among parties], memos & progress reports (Fig. 96), Gantt chart, airports (Fig. 175), etc.
	Product	Drawings, data, prototype, requirements, WBS, schedules, engineering bill of materials, manufacturing bill of materials, production site locations and layouts, life cycle costing, calculations (Fig. 86), etc.
	Project	Aircraft design related project, phased project planning, project skills, project management, multidisciplinary design projects, project objectives, etc.
	Quality	Quality characteristics, quality function deployment (QFD), quality assurance, and quality system requirements
	Reliability	Reliability, security & reliability, safety & reliability, dependability & reliability (competence), etc.
	Requirement	Range (km), number of seats, payload (kg), etc.
	Resource	Cognitive resources, human resource, design facility, etc.
	Service	Serviceability, Electronic Systems Services, processing services for components (e.g., shot peening, heat treatment, plating, coating, etc.), entry into service, service timeline, etc.
	Stakeholder requirement	Industry requirements, comfort, safety, security & reliability, cost and timely delivery, value-driven design, customer specifications, etc.
	Standard	Standard components (e.g., hardware and wiring or harnesses), well accepted standards, standard English, etc.
	System	Aircraft, training (learning), support, facilities, personnel, etc.

	System element	Environmental segment, avionics segment, electrical segment, interior segment, mechanical segment, propulsion segment, auxiliary segment, airframe, etc.
	System requirement	Training (learning), geometry construction, systems architecture, structures, weight & balance, aerodynamics, propulsion, stability & control, operational performance, noise & emission, economics, etc.
	System-of-interest	Aircraft, training (learning), support, facilities, personnel, etc.
	Trade-off	Weight & balance, cost and timely delivery, design space / technology insertion (Fig. 174), etc.

6.4.1.3 Human environment

The human environments include all the human beings but particularly the human users of an artifact (Zeng, 2015). Concepts in the proposed core ontology related to the human environment are summarized in Table 37.

Table 53 Human environment and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Human environment	Acquirer	Airline, defense, etc.
	Customer	End customers, passengers
	Operator	Passengers, crews, pilots, etc.
	Organization	Government, industry partners, OEM, etc.
	Party	Industry partners, government, airlines, universities, etc.
	Stakeholder	Students, professors, curriculum developers, government through specific institutions (e.g., FAA), international educators, competitors (Fig. 86), etc.
	Supplier	OEM, tier 1, tier 2, tier 3, tier 4, etc.
	User	Passengers, crews, pilots, etc.

6.4.1.4 Design process

The design process are the activities (i.e., environment analysis, conflict identification, and solution generation) executed to change an existing environment to a desired one by creating a new artifact into the existing one (Zeng, 2015). Concepts in the proposed core ontology related to the design process are summarized in Table 38.

Table 54 Design process and PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Design process	Activity	50 steps (Fig. 98), design methodology
	Process	Aircraft design requirement, conceptual design, preliminary design, detail design, etc.; design methodology
	Quality management	Quality system requirements [ISO 9001 / AS9100]

6.4.1.5 Life cycle

Life cycle are phases (stages) occurring in the life of a product (e.g., design, manufacturing, sales, transportation, use, maintenance, and recycle) (Z. Chen & Zeng, 2006). Concepts in the proposed core ontology related to the life cycle are summarized in Table 39.

Table 55 Life cycle and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Life cycle	Life cycle	Life cycle perspective, verification of system requirements in the life cycle, life cycle costing, aircraft life cycle, life cycle phases, etc.
	Life cycle model	Life cycle model [e.g., V-mode]
	Stage	Concept and design, manufacturing, installation/integration and test, operation, maintenance, etc.
	System life cycle processes	Aircraft life cycle process (Fig. 74 to Fig. 175): research and development, production, operation and maintenance, phase out / disposal.

6.4.1.6 Discussion

Data analysis proves that the concepts in the proposed core ontology are valid and necessary to represent the domain of integrating learning through design methodologies in aircraft design. Evidence of proof is summarized for EBD root concepts and concepts in the proposed core ontology from Table 35 to Table 39. Therefore, each concept is valid and needed to communicate and understand learning in aircraft design. As a result, the proposed core ontology can be interpreted a valid minimum information model to communicate and understand the context of learning in aircraft design.

In general, the subjective method of characterization enables to allocate the same concepts in more than one concept in the proposed core ontology. This observation was also found and discussed in data analysis in Chapter 5.

6.5 Conclusions

In this case study, the integration of learning in aircraft design is analyzed. This analysis involves the study of learning, civil airplane design, design methodologies and their integration. Civil airplane design is a complex task that considers different aspects of the natural environment, human resources, systems & subsystems, design methodologies, and life cycle perspective. The case study provides guidance to formulate learning in civil airplane design through the use of design methodologies. This chapter concludes with a design process of 50 steps that become a framework to define learning in civil aircraft design. These steps become the foundation to develop a desired design methodology for learning in aircraft design. This goal can be achieved addressing the identified conflicts and developing the proposed solutions.

The case study proves that EBD root concepts and the concepts in the proposed core ontology are effective to communicate and understand learning in aircraft design, subsequently the broad context of requirements in this kind of engineering projects. All these concepts are implicit in engineering communication during learning in aircraft design. Hence, the concepts conform a common vocabulary during learning in aircraft design. These concepts will increase the likelihood to improve communication and understanding during learning in aircraft design projects. So, the proposed core ontology can be interpreted as a valid minimum information model to communicate and understand the context of learning in aircraft design.

There are limitations in data analysis. One limitation is that the characterization of concepts was not exhaustive. Exhaustive characterization of the concepts may help to interpret the relative importance of each concept. The relative importance of each concept provides guidance about where to prioritize more attention while communicating and understanding requirements about learning in aircraft design. At the current stage of development of the ontology, it was considered more important to identify the right concepts than identifying their relative importance. The right concepts shall be understood properly before trying to understand their relative importance. The remaining case study in Chapter 7 will seek to understand the concepts more properly from a different engineering domain (i.e., healthcare), while future work may involve defining the relative importance of each concept. In addition, future work needs to investigate specific system life cycle analyses and communication mechanism during learning in aircraft design projects. Finally, future work can also try to tackle the identified problems in characterization discussed in Section 6.4.1.6.

Chapter 7: Case study 3 - Designing the right framework for healthcare decision support

7.1 Introduction

The contribution of this chapter is to validate the proposed core ontology in Chapter 4. To achieve the needed validation, this chapter employs a case study titled *Designing the right framework for healthcare decision support* as a source of content analysis to facilitate retrospection. The objective of this case study was to *"Design the right framework for healthcare decision support"*. This chapter corresponds to *Designing the right framework for healthcare decision support* in Fig. 22.

To validate the proposed core ontology, the rest of the chapter is organized as follows. Section 7.2 presents a general background in the context of integrating learning through design methodologies in aircraft design. Section 7.3 describes data collection employing EBD methodology. Section 7.4 discusses data analysis. Finally, Section 7.5 ends with conclusions.

7.2 General background

Today it is extremely important to study healthcare delivery infrastructure due to the increasingly changing atmosphere of healthcare delivery. For example in the US, with the introduction of the Affordable Care Act (Koh & Sebelius, 2010) and HITECH (Blumenthal, 2009), it has become increasingly important for healthcare providers to adopt a healthcare delivery system that is not only affordable but also that satisfies the criteria of meaningful use. While attempting to satisfy the aforementioned criteria physicians also have to be mindful of financial return of investment and to balance usability and security of the healthcare systems (Zhang & Liu, 2010). Canada also faces a similar situation than in the US (Government of Canada, 2018). Indeed, healthcare challenges are global (WHO, 2018). The challenges trigger the need to understand the context of health systems in order to derive the right framework for healthcare decision support.

7.3 Data collection

The process of data collection was initiated informally through email starting on January 20, 2016. On January 25 of the same year, title, abstract, and sections of the paper were created by Dr. Varadraj Gurupur from Health Management and Informatics, University of Central Florida, Orlando, FL, USA. The title, abstract, and sections were sent through email from this author to the second author of the paper (author of this thesis). Emails facilitated to create a shared understanding of the context and preliminary aspects of the content in the paper.

After initial emails, data collection followed EBD methodology. Details about execution of EBD methodology are discussed in the rest of this section. In particular, Section 7.3.1 presents environment analysis. Section 7.3.2 discusses conflict identification. Finally, Section 7.3.3 introduced solution generation. Section 7.3.2 and Section 7.3.3 are expanded in this thesis to have a complete application of EBD methodology.

7.3.1 Environment analysis

After an initial iteration of creating shared understanding, data collection followed the question-asking strategy in EBD methodology (Zeng, 2011). The strategy is the same applied in Chapter 5. The major tools in EBD methodology to implement the strategy are: ROM (Zeng, 2008) and the question asking generation process (Wang & Zeng, 2009).

The question-asking strategy started by creating a ROM representation from the objective of the case study, i.e., *design the right framework for healthcare decision support.* The objective of the case study corresponds to the title of the original published article (Gurupur & Gutierrez, 2016). Based on the objective, the ROM representation in Fig. 69 was created. The ROM representation removes the part-of-speech related to articles defined in the case study objective. The ROM representation was used to generate questions. The questions were classified into 4 groups: 1) general questions about healthcare, 2) general questions about healthcare decisions, 3) general questions about healthcare decision support, and 4) general questions about the framework. The questions were reviewed and agreed between the two authors of the original article (Gurupur & Gutierrez, 2016). The process of creating shared understanding about the questions for the original article lasted from January 26 to January 27 in 2016. Shared understanding about the context to review and agreement of the questions was supported by using the framework in Fig. 102. The reviewed and agreed questions with their respective assigned groups are defined in Table 56. These questions were allocated originally into the suggested sections of the original article. Table 56 defines the sections where the questions were allocated in this chapter. The sections in Table 56 have only small variations to the sections in the original article, which is expected not to hinder understanding and application of the idea.

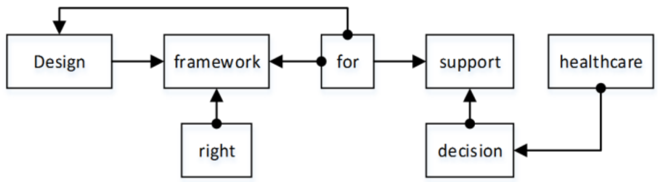


Fig. 101 ROM representation for the case study objective

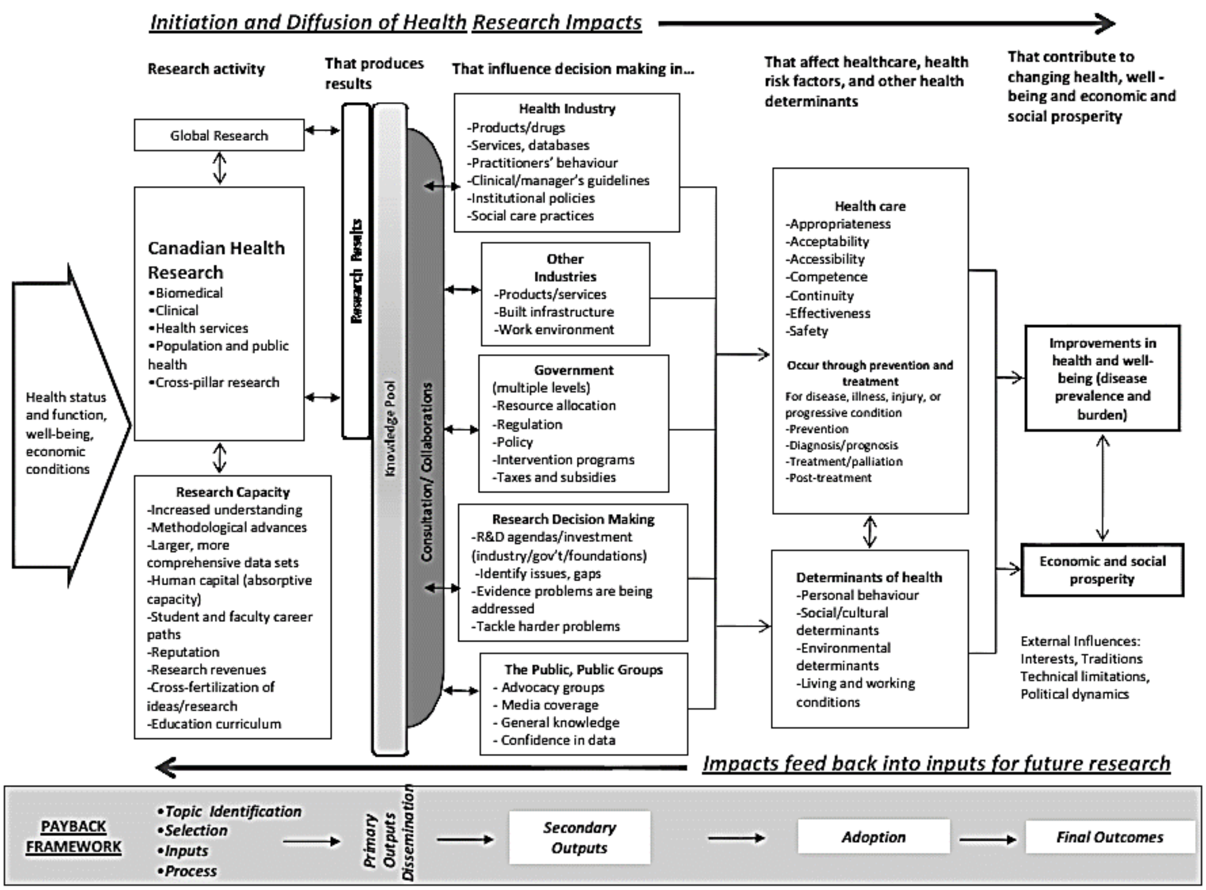


Fig. 102 Impact framework of the Canadian Academy of Health Sciences (CAHS) (2009, p. 18)

Table 56 Generated questions and assigned groups

Group	Generated question	Section
General questions about healthcare	1. Why to study healthcare? 2. What is/are the definition and components of healthcare in the paper context?	Section 7.3.1.1
General questions about healthcare decisions	3. Why to make the decisions of healthcare? 4. What is/are the definition and components of healthcare decisions? 5. What are the types of decisions to be made in healthcare? 6. Who are the stakeholders of healthcare decisions? 7. Who make the decisions of healthcare? 8. How/when/where to make the healthcare decision? 9. What are the criteria to evaluate the effectiveness and efficiency of healthcare decisions?	Section 7.3.1.2
General questions about healthcare decision support	10. Why to support the healthcare decisions? 11. What is/are the definition and components of healthcare decision support? 12. What are the types of decisions to be made for healthcare decision support? 13. Who are the stakeholders for healthcare decision support? 14. Who make the decisions for healthcare decision support? 15. How/when/where to support the Healthcare Decision? 16. What are the criteria to evaluate the effectiveness and efficiency for healthcare decision support?	Section 7.3.1.3
General questions about the framework	17. Why to design the right framework for healthcare decision support? 18. How to design the right framework for healthcare decision support? 19. What is/are the definition and components of the right framework? 20. What is the criteria to validate the right framework?	Sections 7.3.1.4, 7.3.1.5, and 7.3.1.6

Questions were answered as defined in Table 56. To divide the work on the original article, the created questions and defined sections were used. By February 22, 2016, the authors completed to answer the questions. Until that date, all data collection through the generated questions was completed.

7.3.1.1 Healthcare

In general, healthcare is the maintenance and improvement of physical and mental health[46], especially through the provision of medical services (SEBoK Author Team, 2018). Different organizations have attempted to define healthcare and its components. These organizations are at diverse levels of abstraction such as global (e.g., World Health Organization), specific countries' organizations (e.g., Organisation for Economic Co-operation and Development), nationwide (e.g., USA and Canada), regional (states or provinces) and more micro levels (hospitals, clinics or home care). The following paragraphs develop the three first levels.

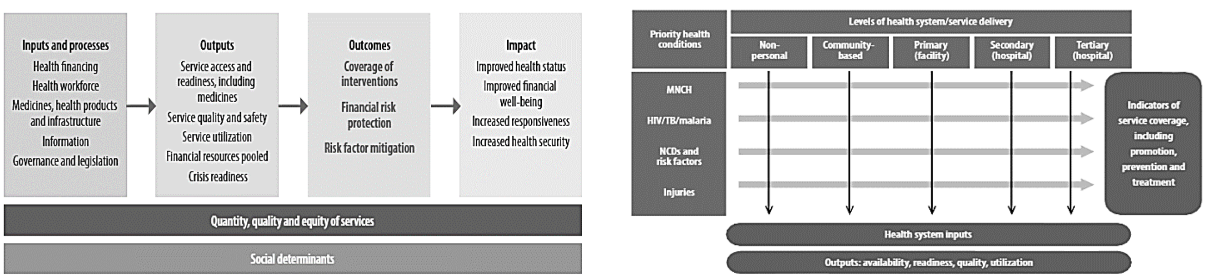


Fig. 103 WHO representations of healthcare: a representation of the results chain for universal health coverage, focusing on outcomes (left side); and a framework for measuring and monitoring the coverage of health services (right side) (World Health Organization, 2013, pp. 9, 15)

The WHO (World Health Organization, 2013, p. xi) relates the world health to health coverage. The WHO defines health coverage in terms of provision and access to high-quality health services, and financial risk protection for people who need to use the services and overall society. In addition, health services include methods for promotion, prevention, treatment, rehabilitation and palliation, encompassing health care in communities, health centers and

[46] Health is a condition of physical, mental, and social well-being and the absence of disease or other abnormal condition. Health is not a static condition. Constant change and adaption to stress result in homeostasis (i.e., a relative constancy in the internal environment of the body, naturally maintained by adaptive responses that promote heathy survival). Thus, the states of health or disease are the expressions of the success or failure experienced by an organism in its efforts to respond adaptively to environmental challenges – by O'Toole (2013).

hospitals. Health services also mean acting on social and environmental determinants both within and beyond the health sector. Besides these components to define healthcare, other important components are health systems, input processes, outputs, outcomes, impact, social determinants, and quality and quantity; refer to Fig. 103.

The Organisation for Economic Co-operation and Development (OECD, 2015a, p. 13) defines health using indicators of health status and health systems, where the goal of the latter is to improve the health status of the population. The OECD (2015a, p. 13) uses the framework in Fig. 104 to assess the performance of health systems. The framework is based on the OECD Health Care Quality Indicators project (Arah, Westert, Hurst, & Klazinga, 2006; Kelley & Hurst, 2006). As each country in the OECD has its own regulations, but similar human needs, the scope in this case study is narrow down to the US and Canada for practical purposes. Other international frameworks are discussed by The European Observatory on Health Systems and Policies (2013).

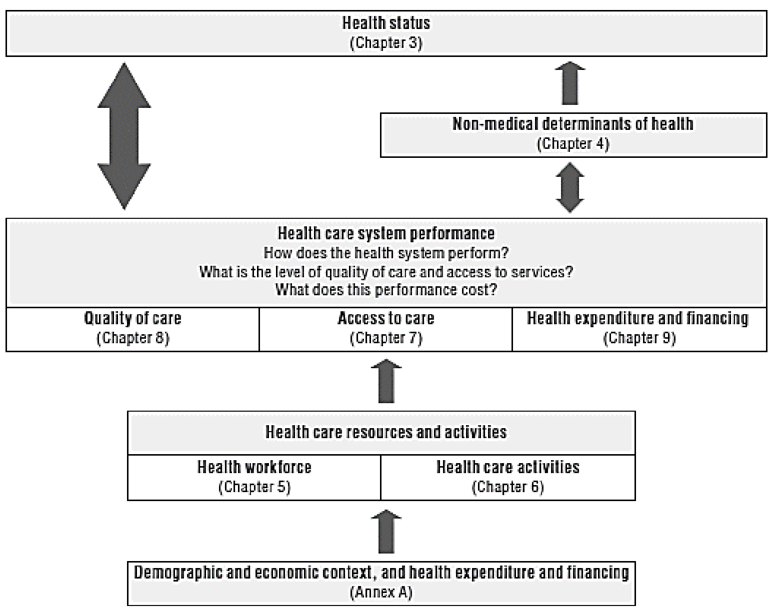


Fig. 104 OECD (2015a, p. 14) conceptual framework for health system performance assessment

The US Department of Health & Human Services defines healthcare in accordance with its strategic plan (U.S. Department of Health & Human Services, 2016b), the Affordable Care Act (U.S. Department of Health & Human Services, 2016a), the US National Healthcare Quality and Disparities reports (Agency for Healthcare Research and Quality, 2015a, 2015b), and others ("Healthcare Research and Quality Act of 1999," 1999). Using these documents as bounding terms, the US Department of Health & Human Services defines healthcare in terms of access to care (primary and preventive), access to information and data, scientific knowledge, research networks, people (patients, consumers, providers, purchasers, practitioners, policy makers, general authorities and educators), social security, private-public partnerships, health insurance more affordable, technologies (e.g., information systems), facilities, equipment, methods, best practices, healthcare outcomes, cost, utilization, and quality (safety, effectiveness, efficiency, and competency) among others for Americans. Fig. 105 illustrates conceptual relationships between the components in the US healthcare system.

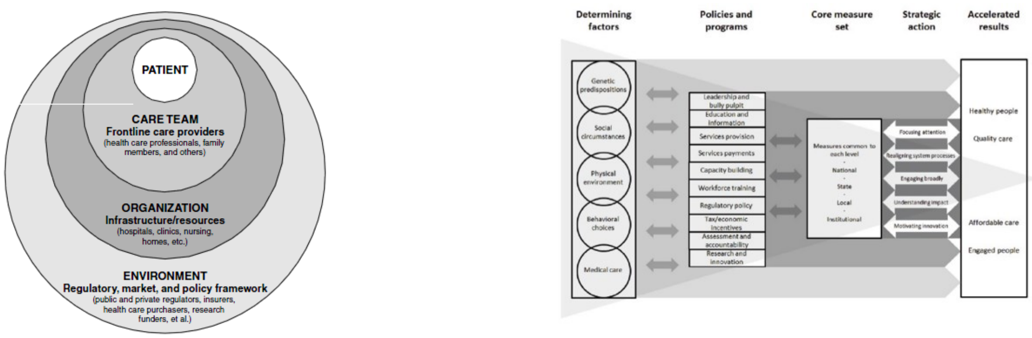


Fig. 105 Conceptual drawing of a four-level health care system by the National Academy of Engineering and Institute of Medicine (2005, p. 20) at the left side, and core measures as levers for enhancing the impacts of the key determinants of health by the Institute of Medicine (2015b, p. 102) at the right side

Although Canada and the US does not share the position of universal access policy in their respective healthcare systems[47], these countries have shared cultural and economic spheres, and common history of medical care delivery (Maioni, 2015, pp. 61-77; Nadeau, Soroka, Maioni, Bélanger, & Pétry, 2015). Along this stream, the health care systems in Canada is framed by the Canada Health Act (Health Canada, 2010a, 2012a). The act defines healthcare using the main terms such as Government of Canada, provinces, Canadians and its well-being, health services, sickness, diseases, income groups, social, environmental and occupational causes of disease, cooperative partnership of governments, health professionals, voluntary organizations, and individual Canadians, continued access to quality health care without financial or other barriers, Canada transfer health (cash contribution), extended health care services (i.e., nursing home intermediate care services, adult residential care services, home care services, and ambulatory care services), extra-billing, health care insurance plan, law of the province, hospitals, hospital services (e.g., meals, nursing, laboratory, drugs, operating room and other facilities, equipment and

[47] From the patient point of view, check the Department of Health & Human Services USA (2016) and Health Canada (2012b) roadmaps to health.

supplies), insured health services, insured person, minister of health, physician services, resident, surgical-dental services, user charge, consultation process, exceptions/limitations and regulations (Government of Canada, 2016). In addition, the act indicates that each province throughout a fiscal year must satisfy the criteria of public administration, comprehensiveness, universality, portability, and accessibility to get full cash contribution from the government. Fig. 106 shows two frameworks illustrating the relationships between the main components included in the Canada Health Act.

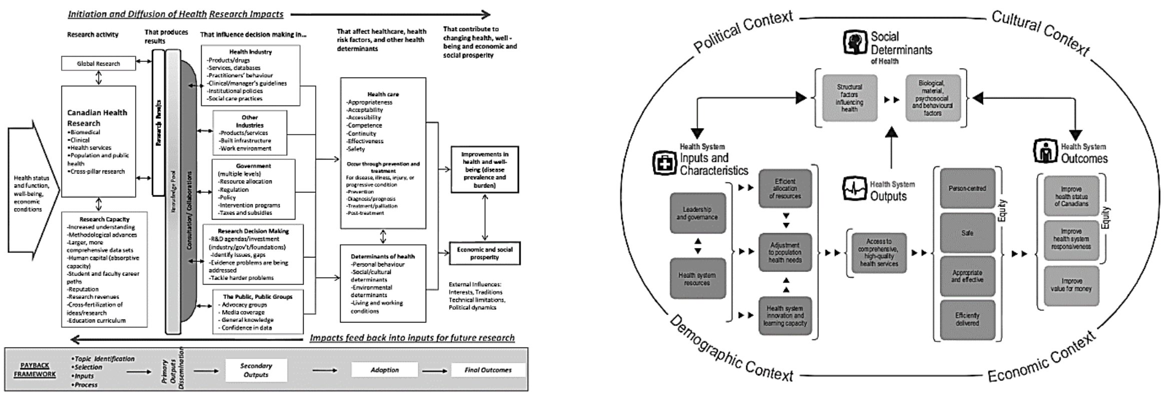


Fig. 106 Impact framework of the Canadian Academy of Health Sciences (CAHS) (2009, p. 18) at the left side, and new health system performance measurement framework of the Canadian Institute for Health Information (CIHI) (2013) at the right side

The frameworks from Fig. 103 to Fig. 106 depict the big picture of healthcare. However, it is important to state the existence of structures and relationships within each component of the frameworks as illustrated in the left side of Fig. 105. For example, Fig. 107 illustrates a hospital performance framework that aligns with the health system performance measurement framework in Fig. 106. In other words, Fig. 107 deploys down the strategy of the country-wide health system performance measurement framework in the right side in Fig. 106 to the hospital level.

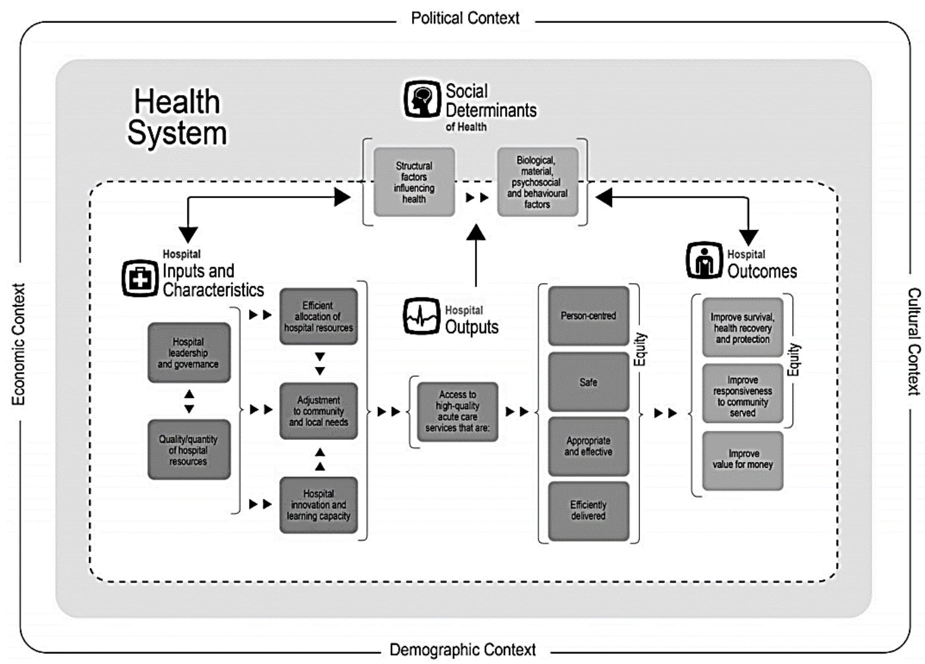


Fig. 107 Hospital performance framework (Canadian Institute for Health Information (CIHI), 2015, p. 31)

In general, the components of healthcare can be divided into three groups: natural, built, and human. Natural deals with health, diseases and well-being of the person (i.e., human body). Built refers to health services, hospital services, laboratories, technologies, prevention methods, treatments, treatment methods, insurance, outcomes, contexts (e.g., political, cultural, demographic, and economic), etc. Human denotes patients, consumers, providers, purchasers, practitioners, policy makers, general authorities, educators, and general population. Natural, built, and human define the three types of environments in EBD theory.

7.3.1.2 Healthcare decisions

Decisions are types of statements in which a choice between two or more possible outcomes controls which set of actions will result (ISO/IEC/IEEE, 2017). As a result, healthcare decisions refer to types of statements in which a choice between two or more possible outcomes controls which set of actions will result for the maintenance and improvement of physical and mental health, especially through the provision of medical services.

Understanding healthcare decisions is a complex subject. To achieve such understanding, healthcare decisions are investigated through a series of questions. The questions are: 1) what the components of healthcare decisions are, 2) what types of decisions are made in healthcare, 3) who the stakeholders of healthcare decisions are, 4) who makes decisions of healthcare, 5) how/when/where to make healthcare decisions, and 6) what criteria are to evaluate the effectiveness and efficiency of healthcare decisions. Each of the questions is answered in the remaining of this section.

7.3.1.2.1 What are the components of healthcare decisions?

Considering Fig. 103 to Fig. 107, healthcare decisions occur at distinct levels of the healthcare system involving different stakeholders, outcomes, and criteria. Decisions are at the global level, the national level (e.g., government and public), the industry level, and the patient level in hospitals, clinics or homes. The composition and interactions of all these components and stakeholders make healthcare decisions complex. Healthcare decisions are moving towards centralized decision-making structures (Health Canada, 2012a; OECD, 2013).

7.3.1.2.2 What are the types of decisions to be made in healthcare?

There are several decisions made in the healthcare system. The decisions happen at distinct levels at different decentralized parts of the system, so understanding the truth of these highly complex systems is not an easy task (Advisory Panel on Healthcare Innovation, 2015, p. 4; Carson, Nossal, & Dixon, 2015, pp. 1-13; Institute of Medicine, 2013b, pp. 2-4, 77-91). Some examples of decisions in healthcare are: selecting and implementing the US nation-wide metric (Institute of Medicine, 2015b); identifying, assessing, and managing health risk from sources such as water, air, diseases, toxic substances, consumer products, workplace substances, food, drugs (pharmaceuticals), medical devices and pesticides (Health Canada, 2000); deciding about vaccine programs (Public Health Agency of Canada, 2015); replacing earlier treatment methods or providing new treatment options with new drug therapies (Health Canada, 2004); defining and interpreting acts and regulations (Health Canada, 2005); innovating healthcare (Advisory Panel on Healthcare Innovation, 2015); respecting privacy, information, sustainable development and others (Health Canada, 2015b); improving diagnosis (National Academies of Sciences, Engineering, & Medicine, 2015); scheduling and access (Institute of Medicine, 2015a); investing in global health systems (Institute of Medicine, 2014d); evaluating design for complex global initiatives (Institute of Medicine, 2014b); balancing coverage and cost (Institute of Medicine, 2012); designing best care at lower cost (Institute of Medicine, 2013a); answering questions regarding to geographic variation in healthcare spending, utilization and quality (Institute of Medicine, 2013c); planning health professional education (Institute of Medicine, 2010, 2014c); planning the nursing profession (institute of Medicine, 2011); establishing transdisciplinary professionalism for improving health outcomes (Institute of Medicine, 2014a); building a better delivery system (National Academy of Engineering, 2010; National Academy of Engineering & Institute of Medicine, 2005); planning computations technology for effective health care (National Research Council, 2009); supporting cognitive engineering application in health care (National Academy of Engineering, 2009); engineering a learning healthcare system (Institute of Medicine & National Academy of Engineering, 2011); recommending strategies and priorities for information technology at the centers for Medicare and Medicaid Services (National Research Council, 2012, pp. 111-122); etc. Although the list of previous endeavors in healthcare decisions is not exhaustive, it shows the broad variety of decisions to be made in healthcare.

7.3.1.2.3 Who are the stakeholders of healthcare decisions?

Considering the broad scope of decisions in health and healthcare systems, each of them implies several general and specific stakeholders. The Institute of Medicine (2013b, pp. 79-82) in the US suggests as stakeholders people and institutions in the following categories: 1) patients, consumers, caregivers, and the public; 2) health care professionals (physicians, nurses, pharmacists, and others); 3) hospitals and health care delivery organizations; 4) payers; 5) public health agencies; 6) regulators; 7) communication professionals and the media; 8) community-based organizations; 9) states (legislators, governors, executive agencies); and 10) federal government (legislators, executive agencies).

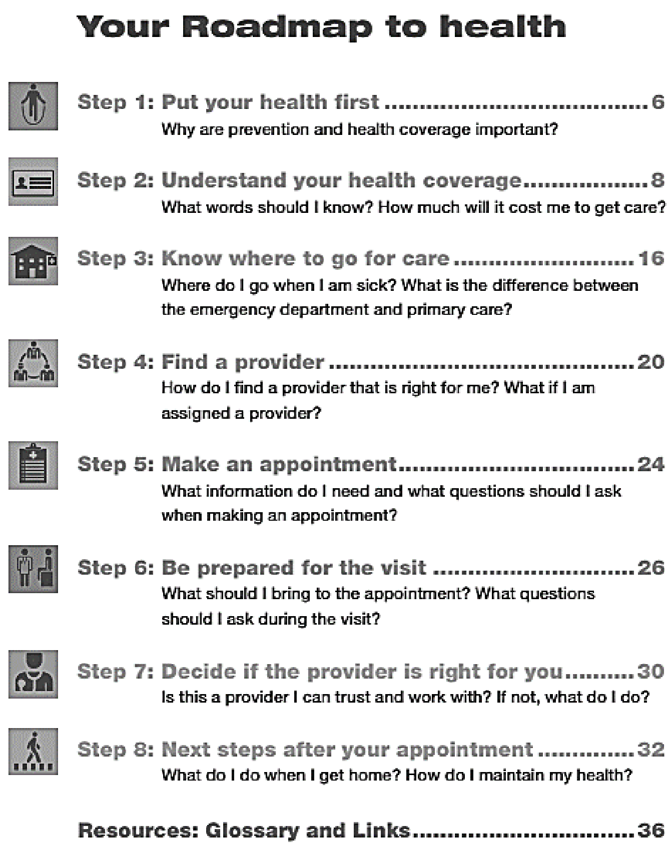
7.3.1.2.4 Who makes healthcare decisions?

Based on the Institute of Medicine (2008, pp. 21-22), healthcare decisions are made by multiple people, individually or collaboratively, in multiple contexts for multiple purposes. The institute adds that *"Decision makers are likely to be the consumer choosing among health plans, patients or the patients' caregivers making treatment choices, payers or employers making health care coverage and reimbursement decisions, professional medical societies developing practice guidelines or clinical recommendations, regulatory agencies assessing new drugs or devices, and* *public programs developing population-based health interventions. Every decision maker needs credible, unbiased, and understandable evidence on the effectiveness of health care services".*

7.3.1.2.5 How/when/where to make the healthcare Decision?

Providing direct answer to this question requires to break down healthcare decisions and to find the relevant stakeholders, information (e.g., evidence), outcomes, and criteria. For practical purposes, the example of setting priorities for evidence-based assessment in healthcare is used. Under this consideration, the Institute of Medicine (2008, pp. 57-77) in the US recommends the appointment of an independent Priority Setting Advisory Committee (PSAC) to develop and implement a process for a national clinical assessment program. The institute complements that the committee should ensure a balance of expertise and interests with minimal bias due to conflict of interest in order to adhere the process to principles of consistency, efficiency, objectivity, responsiveness, and transparency. As a result, the institute indicates that the process should be open, predictable, and explicitly defined, with fully documented standards and simple and effective procedures to preserve the available resources. The highest priorities topics should consider: *1) how well the topic reflects the clinical questions of patients and clinicians, and 2) the potential for the topics to have a strong impact on clinical and other outcomes that matter the most to patients"* (Institute of Medicine, 2008, p. 57). Depending on the type of question to made a decision and the timeframe, the Institute of Medicine (2008, pp. 90-92, 102-104) indicates that there are specific types of evidences that can represent different level of quality for the answer.

At the patient level, a roadmap to health for people can be considered as the life cycle of healthcare, and so for healthcare decisions. The roadmap defines steps and questions to be answered during the life cycle of healthcare. Such steps and questions are defined in Fig. 108. Evidently, healthcare decisions, from a patient point of view, are needed at each step of the roadmap. Patients need to have the right information to support their decisions along the roadmap to improve effectively and efficiently their health problems.


Your Roadmap to health

Step 1: Put your health first 6
Why are prevention and health coverage important?

Step 2: Understand your health coverage.................. 8
What words should I know? How much will it cost me to get care?

Step 3: Know where to go for care 16
Where do I go when I am sick? What is the difference between the emergency department and primary care?

Step 4: Find a provider 20
How do I find a provider that is right for me? What if I am assigned a provider?

Step 5: Make an appointment.................................. 24
What information do I need and what questions should I ask when making an appointment?

Step 6: Be prepared for the visit 26
What should I bring to the appointment? What questions should I ask during the visit?

Step 7: Decide if the provider is right for you.......... 30
Is this a provider I can trust and work with? If not, what do I do?

Step 8: Next steps after your appointment 32
What do I do when I get home? How do I maintain my health?

Resources: Glossary and Links................................ 36

Fig. 108 Patient roadmap to health (Department of Health & Human Services USA, 2016)

7.3.1.2.6 What are the criteria to evaluate the effectiveness and efficiency of healthcare decisions?

Considering the big picture of healthcare, several indicators are used to evaluate the effectiveness and efficiency of healthcare decisions. Health decisions are evaluated in the World Health Statistics using criteria such as life expectancy and mortality, cause-specific mortality and morbidity, infectious diseases, health services coverage, risk factors, health systems (i.e., workforce, infrastructure and technologies, and essential medicines), health expenditures, health inequities, and demographic and socioeconomic context (World Health Organization, 2015). The OECD (2015a) organized the criteria to evaluate the effectiveness and efficiency of healthcare decisions in terms of health status (i.e., life expectancy and mortality), risk factors to health, access to care, quality of care, health workforce, health care activities, pharmaceutical spending, pharmaceutical sector, non-medical determinants of health, health expenditure and financing, ageing and long-term care, and demographic and socioeconomic context. The Agency for

Healthcare Research and Quality (2015b) in the US evaluates healthcare decisions around concepts of access to care, quality of care (i.e., processes of care, outcomes of care, patient perception of care, and infrastructure), disparities in care, and the NQS (National Quality Strategy) priorities. More specifically, the agency uses metrics such as access to health care, patient safety, person and family centered care, care coordination, effective treatment, healthy living, care affordability, and priority populations. In Canada, the main indicators to evaluate healthcare decisions are health status, health system responsiveness, value for money, and equity in health status and responsiveness (Canadian Institute for Health Information (CIHI), 2015, p. 29). CIHI (2015, pp. 66-68) defines more specifically subcomponents of the indicators. It can be understood that despite of difference approaches to finance healthcare systems, several countries share similar indicators to evaluate the effectiveness and efficiency of healthcare decisions.

7.3.1.3 Healthcare decision support

Support is a set of activities necessary to ensure that an operational system or component fulfills its original requirements and any subsequent modifications to those requirements (ISO/IEC/IEEE, 2017). Thus, healthcare decision support is a set of activities necessary to ensure that healthcare decisions or their components fulfills its original requirements and any subsequent modification to those requirements.

Healthcare decision support follows healthcare decisions. As healthcare decisions happen at distinct levels in healthcare, healthcare decision support plays a role in each of them. This section links healthcare decisions to healthcare decision support answering the questions: 1) *what are the components of healthcare decisions support? 2) what are the types of decisions for healthcare decision support? 3) who are the stakeholders for healthcare decision support? 4) who uses healthcare decision support? 5) how, when, and where to support healthcare decisions? and 6) what are the criteria to evaluate the effectiveness and efficiency of healthcare decision support?* The answers to these questions are presented in Section 7.3.1.3.1 to Section 7.3.1.3.6 respectively. Considering the big scope of healthcare and healthcare decision support, some questions are only partially answered with specific examples from the literature. This strategy is used to limit the scope of the answer for practical purposes, but it is expected to depict a clear guidance for the reader to address other components of the question.

7.3.1.3.1 What are the components of healthcare decision support?

This question is answered in term of components and opportunities. They are introduced in the same previous order.

Table 57 NHII components and its respective sub-components by The National Academy of Engineering and Institute of Medicine (2005, pp. 19-22, 65-81)

US National health care information infrastructure (NHII) – Components	Sub-components
1. Health care data standards and technical infrastructure	1.1. Data interchange formats 1.2. Terminologies 1.3. Knowledge representations
2. Core clinical applications	2.1. EHR 2.2. CPOE 2.3. Digital sources of medical evidence 2.4. Decision-support tools 2.5. Human-computer interfaces 2.6. Software dependability
3. Information and communication systems (hardware and software)	3.1. Bandwidth requirement and availability 3.2. Latency in transmission throughout the network 3.3. Continuous availability of the network 3.4. Confidentiality and security of data 3.5. Ubiquity of access to the network
4. Levels	4.1. Individual patient 4.2. Care team (professional care provides – e.g., clinicians, pharmacists, and others), the patient and family members 4.3. Organization (e.g., hospital, clinic, nursing home, other infrastructures and complementary resources) 4.4. Political and economic environment (e.g., regulatory, financial, payment regimes, and markets)

In general terms, the US national health care information infrastructure (NHII) is defined as a set of components linked explicitly to health care delivery processes as follows (National Academy of Engineering & Institute of Medicine, 2005, p. 64):

"The NHII is defined as "a set of technologies, standards, applications, systems, values, and laws that support all facets of individual health, health care, and public health" . . . It encompasses an information network based on Internet protocols, common standards, timely knowledge transfer, and transparent government processes with the capability for information flows across three dimensions: (1) personal health, to support individuals in their own wellness and health care decision making; (2) health care providers, to ensure access to complete and accurate patient data around the clock and to clinical decision support systems; and (3) public health, to address and track public health concerns and health education campaigns".

The National Academy of Engineering and Institute of Medicine (2005, pp. 67-81) divided the NHII components into three interrelated categories: 1) health care data standards and technical infrastructure; 2) core clinical applications; and 3) information/communication systems. Healthcare standards are defined as data interchange formats, terminologies, and knowledge representations. Core clinical applications are composed of EHRs, CPOE (computerized physician order entry), digital sources of medical evidence, decision-support tools, human-computer interfaces, and software dependability. Decision-support tools at core clinical applications are facilitated by the key components of clinical information systems (i.e., the standardization of health care data, the development of digital sources of medical evidence and knowledge, and the creation of EHRs). Information/communication systems are defined in term of a combination of wireless and fixed-line networks using hardware and software which satisfy 5 technical factors: 1) bandwidth requirements and availability, 2) latency in transmission throughout the network, 3) continuous availability of the network, 4) confidentiality and security of data; and 5) ubiquity of access to the network. The three interrelated categories of components provide healthcare decision support at different levels: individual patient, care team, organization, and political and economic environment (refer to left side of Fig. 105). The components and levels are expanded and summarized in Table 57.

The Institute of Medicine and National Academy of Engineering (2011, p. 130) indicates that the US has not fully leveraged the available clinical data to improve the health outcomes of individuals and populations. Some deficiencies are defined as isolated databases, usability issues, inconsistent interoperability standards, privacy and security concerns, culture of health care, complexity of health care including multiple chronic diseases, treatments and technologies available. In response of the increased complexity, engineering principles has not been applied in health care to deal with complex processes. The Institute of Medicine and National Academy of Engineering (2011, p. 132) suggest that clinical decisions support systems needs to take into account both an individual patient-centered view and a population view. They advise that it requires *"getting the right information to the right member at the right time in the workflow or the decision-making process so as to trigger the right event for the care of an individual patient as well as for a population of patients. Another way of framing this point is to ask, what sorts of information do the patient, the clinician, and the healthcare team need to meet their agreed-upon healthcare goals?"* Some opportunities related to clinical decision support systems are summarized in Table 58. Evidence in these developments are noticed in the Strategic goal 1-Objective F of the strategic plan of the U.S. Department of Health & Human Services (2016c), the Canada Health Infoway (2016a), and other initiatives in the OECD (2013, 2015b).

Table 58 Opportunities for clinical decision support systems by the Institute of Medicine and National Academy of Engineering (2011, p. 133)

Opportunity	Description
Reference information and guidance	Clinical evidence sources and guidelines
Direct-to-point clinical decision support	Availability of information
Relevant data presentation	Attention to the human-computer interface
Documentation forms and templates	Integration into the workflow
Order entry facilitator	Integration of decision support at order entry
Protocol and pathway support	A way to facilitate the care process
Reactive alert and reminders	Used judiciously
Use of clinical data	Clinical registries to support planned care model

Electronic health technologies (e.g., electronic health records and telehealth) have been advancing in several countries, including the US and Canada. These advancements have symbolized significant drivers of innovation, sustainability and efficiency in the health care system by improving access to services, patient safety, quality of care, and productivity (Canada Health Infoway, 2016a; Health Canada, 2012a; OECD, 2013, 2015b; U.S. Department of Health & Human Services, 2016c). As these technologies are intended to support healthcare decisions, they also exist at different levels in the big picture of healthcare. Table 59 summarizes some examples of electronic health technologies.

Table 59 Examples of electronic health technologies at different level in the healthcare system (Canada Health Infoway, 2016a; Health Canada, 2010b)

Within country	Within hospitals	Within home	Within primary care
- Electronic health records – EHR (e.g., laboratory information systems, diagnostic imaging systems, registries, interoperable EHR) - Electronic medical records - e-Services (e-referrals, e-prescribing, eMedRec, decision support and workflow, etc.)	- Electronic patient administration systems - Laboratory and radiology information systems - Electronic messaging systems - Telemedicine (e.g., teleconsults, telepathology, teledermatology, etc.)	- Teleconsults and remote vital signs monitoring systems used for diabetes medicine - Asthma monitoring systems - Homes dialysis systems	- Computer systems for patient management, medical records and electronic prescribing - Decision support and workflow at the point of care

7.3.1.3.2 What are the types of decisions for healthcare decision support?

As introduced earlier, there are several types of decisions in healthcare. Healthcare decision support tools could assist all these decisions. For example, the Institute of Medicine (2013a, p. 31) in the US recommended clinical decision support to accelerate integration of the best clinical knowledge into care decisions. The institute suggests that decision support tools and knowledge management systems should be routine features of health care delivery to ensure that decisions made by clinicians and patients are informed by current best evidence. The Institute of Medicine's Roundtable on Value & Science-Driven Health Care has set a goal that by the year 2020, 90% of clinical decisions will be supported by accurate, timely, and up-to-date clinical information, and will reflect the best available evidence (Institute of Medicine & National Academy of Engineering, 2011, pp. xii-xiii).

7.3.1.3.3 Who are the stakeholders for healthcare decision support?

As different types of decisions imply different stakeholders, these stakeholders plus digital technologist developers usually will become the stakeholders for the healthcare decision support. In the case of clinical decision support, the Institute of Medicine (2013a, p. 31) makes explicit guidelines for the following group of stakeholders: 1) clinicians and health care organizations; 2) research organizations, advocacy organizations, professional specialty societies, and care delivery organizations; 3) public and private players; 4) health professional education programs; and 5) research funding agencies and organizations.

7.3.1.3.4 Who uses healthcare decision support?

Decision makers at different institutions and levels use healthcare decision support in their workflows.

7.3.1.3.5 How/when/where to support healthcare Decision?

Considering the big picture, healthcare decisions are supported at all levels at different along the care life cycle. The World Health Summit (2016, pp. 1, 11-23) takes place annually in Berlin, Germany; where global decision makers discuss current challenges and potential solutions emphasizing the increasing role of digital technologies to support healthcare decisions. Country wide, it also remains truth that the decision makers discuss its current challenges and its potential solutions. The U.S. Department of Health & Human Services (2016b, 2016c) every four years updates its strategic plan currently from FY 2014-2018, where it indicates expected roles from digital technologies to support healthcare decisions. Health Canada (2015a) considers a 3-year time period in its report of plan and priorities. The Canadian Institutes of Health Research (2015) plans using a 5 year time frame. These two Canadian institutions also specify the expected role of digital technologies to support their healthcare decisions. At the hospital/clinic level, Mayo Clinic (2015, p. 2) planned for a multiyear investment to fund a new electronic health record and revenue cycle management system, network refresh and data transaction security upgrades. Considering the patient level, the European Commission European Commission (2016, p. 11) in its eHealth action plan 2012-2020 highlights some potential uses for digital, personalized and predicted medicine; advanced analytics, diagnosis, and decision making; new digital media, web and mobile technologies and applications, digital instruments to integrate healthcare and social care systems and support health promotion and prevention; and eHealth systems and services with strong user involvement focusing on interoperability and integration of emerging patient-centric technologies for cost-effective healthcare. Other examples were previously introduced in Table 59.

At the patient level, a roadmap to health for people can be considered as the life cycle of healthcare, and so for healthcare decisions and healthcare decision support. The roadmap defines steps and questions to be answered during the life cycle of healthcare. Such steps and questions are defined in Fig. 108. Evidently, healthcare decision support, from a patient point of view, is applicable to assist and provide answers to the questions in each step of the life cycle of healthcare. The right healthcare decision support provides patients need with the right information to support their decisions along the roadmap in order to improve effectively and efficiently their health problems.

7.3.1.3.6 What are the criteria to evaluate the effectiveness and efficiency for healthcare decision support?

As for healthcare decisions, the criteria to evaluate the effectiveness and efficiency for healthcare decision support is to move forward the status quo of the main health outcomes (Canada Health Infoway, 2016b, p. 4; U.S. Department of Health & Human Services, 2016c). Although efficiency implies being cost wise, it is important to state that evaluating the advantages of making decisions with or without healthcare decision support is significant to justify the investment in healthcare decision support (Health Canada, 2010b; National Academy of Engineering & Institute of Medicine, 2005, pp. 55-58, 63-67).

7.3.1.4 Framework

A framework is defined as a logical structure for classifying and organizing complex information (Marques Pereira & Sousa, 2004). Thus, the right framework for healthcare decision support shall provide a logical structure for classifying and organizing complex information related to health, healthcare, healthcare decisions, and healthcare decision support. To create such kind of framework, this case study adopts EBD methodology as the design methodology. EBD methodology is presented in Section 7.3.1.5.

7.3.1.5 Design methodology: Environment-based design (EBD)

EBD theory and methodology have been applied previously in the context of healthcare, more specifically for medical devices. EBD theory was applied to analyze design requirements for medical devices (M. Chen, Chen, Kong, & Zeng, 2005). EBD theory and methodology have also been applied to the conceptual design of medical devices (S. Tan, Zeng, & Montazami, 2011).

Based on M. Chen et al. (2005), a medical device shall consider requirements from the three environments: natural, built, and human. The three environments interact with the medical devices as depicted in Fig. 109. A medical device shall also consider requirements from its life cycle. The right healthcare decisions support framework can take the place of the medical device. Thus, the right healthcare decision support framework shall also consider requirements from the three environments. Completeness of requirements for the right healthcare decision support shall be assured by considering the life cycle of healthcare (e.g., see Fig. 108).

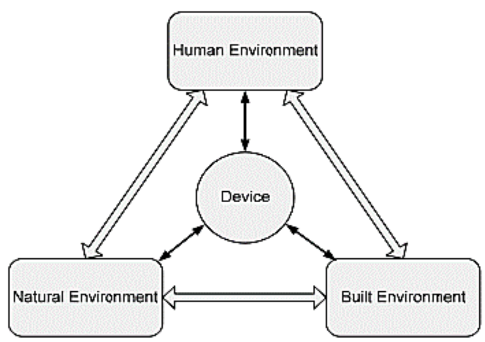


Fig. 109 Environment components for healthcare decision support (M. Chen et al., 2005; S. Tan et al., 2011)

7.3.1.6 The right framework for healthcare decision support

Kovner, Knickman, Weisfeld, and Jonas (2011) have outlined the needs of a healthcare delivery system in the US. However, the authors feel that there is a need to perceive healthcare from a more global perspective. In a more detailed literature, Reid, Compton, Grossman, and Fanjiang (National Academy of Engineering & Institute of Medicine, 2005) describe the engineering aspects of health care delivery systems. The following features play a major role in a healthcare delivery system: a) protecting privacy and security, b) satisfying the criteria of meaningful use, c) interoperability with other healthcare delivery systems, d) incorporating necessary decision support systems and providing the necessary infrastructure to allow the growth of a knowledge base that provides the necessary reasoning to provide decision support, and e) ability to interact with the insurance providers to receive the necessary financial support, which includes generation of the ICD 10 codes based on diagnosis and procedures. Some of the criteria for evaluating the effectiveness and efficiency of healthcare decision support can be listed as follows: a) accuracy of the healthcare decision, b) strength of the knowledge base of the expert system used for healthcare decision support (Hempelmann, Sakoglu, Gurupur, & Jampana, 2016), and c) usability of the decision support system from a user's perspective. With the described features and criteria in mind, the necessary components of the healthcare delivery system would be: i) patient interaction, ii) administrative processing, iii) knowledge base and decision support, iv) XML generators and communication systems to interact with other healthcare delivery systems.

While it is fairly straightforward to choose the components of healthcare delivery, identifying components of healthcare decisions is a complex process. The complexity is mainly due to the fact that requirements for healthcare decision support differs based on several factors such as: a) existing statutory regulations, b) environment of healthcare delivery, c) needs of the patients and caregivers based on demographics, level of education, geographic locations, methods used for communicating with the patients which includes use of telemedicine, remote monitoring, and other such healthcare delivery systems. However, based on the existing literature it may be a good idea to suggest that the necessary elements of healthcare decisions are as follows: a) caregiver decisions, b) diagnostic decisions, c) choosing the right healthcare provider, d) biomedical decisions for laboratories, radiology centers, and other such facilities, and e) administrative decision support for non-clinical personnel. The need for the aforementioned healthcare decisions is mainly due to the following prevailing circumstances: a) need for the reduction in time associated with patient care, b) ease of access to individual healthcare data, and c) complexities emerging from statutory regulations takes a toll on the administrative processes.

The purpose of designing the right framework is to provide a rostrum for the development of decision support systems for healthcare. One of the key factors that challenge the development of the right decision support system is assessing the critical need of decision support for that particular healthcare facility. The critical need could be administrative, financial, patient support, or reduction in time. The first step towards developing the right decision support would be identifying the critical need for developing the decision support mechanism. Once this need has been identified, the software designers and architects would then investigate their time and efforts in developing the right design and architecture to satisfy that critical need. Here the framework can play a pivotal role in aiding the software architects and designers in completing their tasks.

The development of an effective framework involves a) covering all the areas of the critical need, b) developing a structure of the knowledge base that can be rapidly expanded as needed, c) developing an easily modifiable structure for modules that can be used in analysis of data received and knowledge extracted from the knowledge base. This means that the framework must first assess the broad spectrum of the needs, incorporate easily modifiable structures, and allow scalability of knowledge.

The authors strongly feel that a good framework must be more focused on the technical aspects of the decision support rather than focusing on economics. The reason behind this is the fact that robust decision making is possible with a framework that incorporates the attributes previously described in this section. Another important aspect that we would like to bring to notice is the fact that statutory and economic regulations for healthcare may change over time. However, the analytics associated with decision making processes may not change rapidly. Therefore, our focus in on developing a robust technical framework that is scalable, open to changes in technology, and incorporating the key elements of decision making previously described in this section.

The authors identify that there is a need to conceptually divide the framework into two sections: i) clinical decision support and ii) administrative decision support. The components of this framework are as follows: a) Data capture and XML generation, b) Data analysis, c) Result capture and formatting, d) Natural Language Processing, e) Knowledge base, and f) ICD 10 Coding. The components and decision-making information flow are illustrated in Fig. 110. The components in the figure are defined in the remaining of the section.

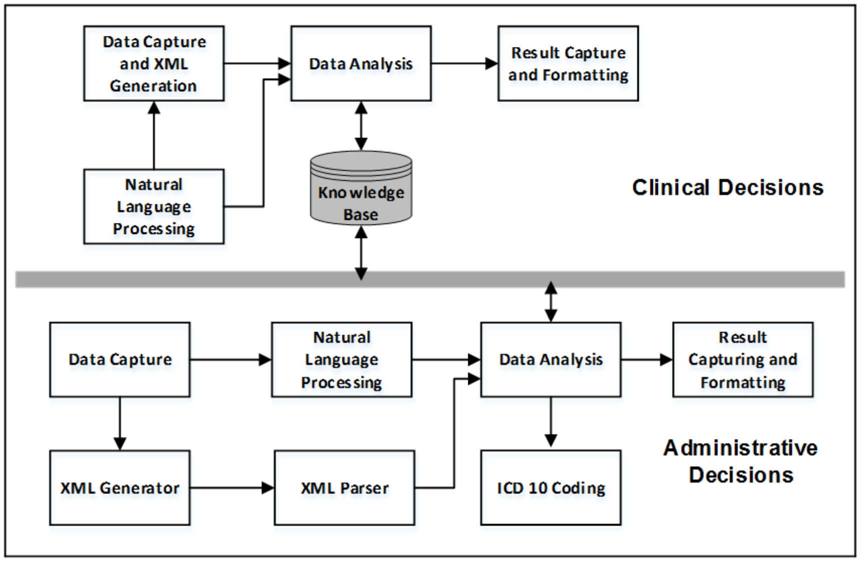


Fig. 110 Environment framework for healthcare decision support (Gurupur & Gutierrez, 2016)

7.3.1.6.1 Data capture and XML generation

The purpose of data capture and XML generation is to collect data in an available format and convert it into an appropriate XML representation. This process may be aided by the use of text mining software to search for appropriate keywords (Karla & Gurupur, 2013).

7.3.1.6.2 Data analysis

The primary objective of the data analysis component of the framework will be to perform the complex computational analysis based on the recommended statistical analysis involving correlation, regression, and computing probabilistic values that would result in efficient decision making.

7.3.1.6.3 Natural language processing

Data available in common language would have to be processed to extract right keywords and sentences to perform data analysis and generate the ICD 10 codes. The purpose of the Natural Language Processing component is to satisfy the aforementioned functionality.

7.3.1.6.4 Knowledge base

One of the key components of every decision support system is a knowledge base. While information contained in the knowledge base should be machine-actable it would be preferable to have it in a form that is human readable. One fine example of this type of approach would be the use of concept maps that has been explained by Gurupur, Sakoglu, Jain, and Tanik (2014). The necessity to develop a visual representation of a knowledge base has been described by Gurupur and Tanik (2012).

7.3.1.6.5 Result capturing and formatting

The results provided by data analysis would have to be formatted and sometimes stored to present it in a suitable format. This process can also involve heavy computation.

7.3.1.6.6 ICD 10 coding

ICD stands for International Statistical Classification of Diseases and Related Health Problems (World Health Organization, 2016a). In general, ICD 10 classifies diseases and related health problems into 5 groups: 1) epidemic diseases, 2) constitutional or general diseases, 3) local diseases arranged by site (i.e., each of the main body systems), 4) developmental diseases, and 5) injuries (World Health Organization, 2016b, pp. 14-15). Based on these 5 groups, ICD 10 defines the 22 categories in Fig. 111. ICD 10 codes would have to be generated to indicate appropriate diagnosis and procedures. This aspect of processing has to be carried out by a separate component of the decision support system.

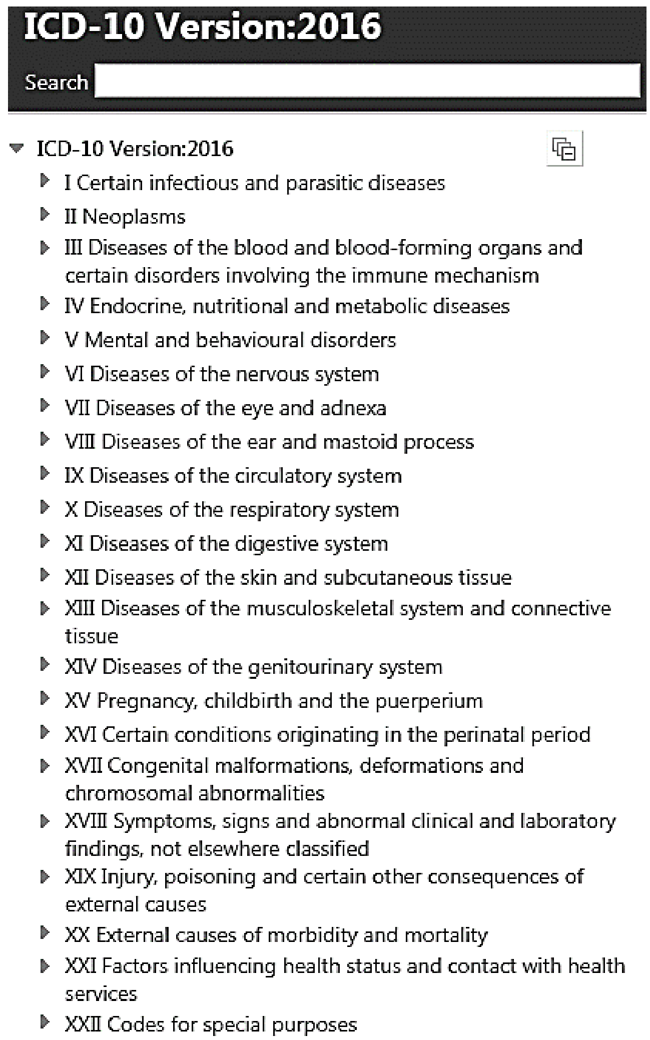


Fig. 111 ICD-10 Version:2016 (World Health Organization, 2016a)

7.3.2 Conflict identification

Conflict identification is intended to identify any gap between the requirements for the framework and the proposed framework. Requirements for the framework comes from the environment, i.e., from the environment components in Fig. 109. Thus, the environment components are the human, natural, and built environment.

The components in the framework in Fig. 110 are considered valid because they satisfy requirements from the human (anatomy defined in ICD 10 codes), natural (diseases defined in ICD 10 codes), and built (rest of components in Fig. 110) environments. From patient point of view, these components are assumed to be the most important ones to conform the right framework for healthcare decision support. Fig. 103 to Fig. 108, Table 57, Table 59 and the alternative components defined in Fig. 112 support the claim that the framework in Fig. 110 has the right components for healthcare decision support. For example, Fig. 112 defines the characteristics of the health internet of things (IoT) environment drafted by the US National Institute of Standards and Technology (NIST) published after the work presented in this case study. Fig. 112 suggests similar solutions to requirements from the environment such as human (people), natural (not specified explicitly), and built (i.e., objects, information resources, systems, and intelligent computing services) than the proposed right framework in Fig. 110; except that the former does not define explicitly ICD-10 codes which are an essential component (i.e., safety and quality) of healthcare decision support (Ghali et al., 2013; Tudorache, Falconer, Nyulas, Noy, & Musen, 2010; Tudorache, Nyulas, Noy, & Musen, 2013). The codes can be part of what Fig. 112 calls structural and semantic standards as an information resource.

Objects	Information Resources	Systems	Intelligent Computing Services
• Home telehealth • Medical devices • Health and wellness products	• HL7 Fast Healthcare Interoperability Resource (FHIR) • Structural and semantic standards (vocabularies, code and value sets) • Actuators that receive commands • Personally worn physiological sensors	• Operations • Payment • Research (system of systems) • Personal health records • Treatment o Electronic health records o Monitoring o Treatment	• Learning Health System o Big data o High performance computing o Knowledge access o Natural language processing o Transformation o Longitudinal monitoring of patients progress o Adverse event monitoring o Translation

People		
• Patients o Patient representatives o Relatives o Health conscious individuals	• Licensed Healthcare Providers: o Audiologists, o Dentists o Dietitians o Optometrists o Physicians o Nurses o Technicians/ Technologists o Therapists	▪ Non-Licensed Healthcare Providers: o Administrative personnel o Aides o Emergency services o Interpreters ▪ Transport personnel ▪ Insurance payers

Fig. 112 Characteristics of the health IoT environment (NIST, 2018, p. 14)

Considering that for the purpose of this case study Fig. 110 defines solutions for requirements coming from the human, natural, and built environment; no conflict is identified at this stage of design. Nonetheless, conflicts may arise in the future when the framework is adapted to specific realities (i.e., detailed design) of healthcare, healthcare decisions, and healthcare decision support.

7.3.3 Solution generation

At this stage of the case study, the generated framework in Fig. 110 is considered to have no conflict between the defined components. However, conflict may arise in the future when the framework is applied to specific cases and detailed design. At this point, other components for the framework can be adapted from Fig. 103 to Fig. 108, Table 57, Table 59 or the alternative components defined in Fig. 112. At that point, conflict identification shall be reevaluated.

Further research about the proposed framework can follow different directions. One direction is to investigate the role of statutory requirements, ease of use and access, and protection of patient data from malicious use. Another direction of research is to implement the framework with the new ICD-11[48] codes. This implementation shall also investigate and integrate the role of statutory requirements, ease of use and access, and protection of patient data from malicious use. A third direction is to align the proposed framework with the life cycle of healthcare from a patient point of view as shown in Fig. 113 or Fig. 108.

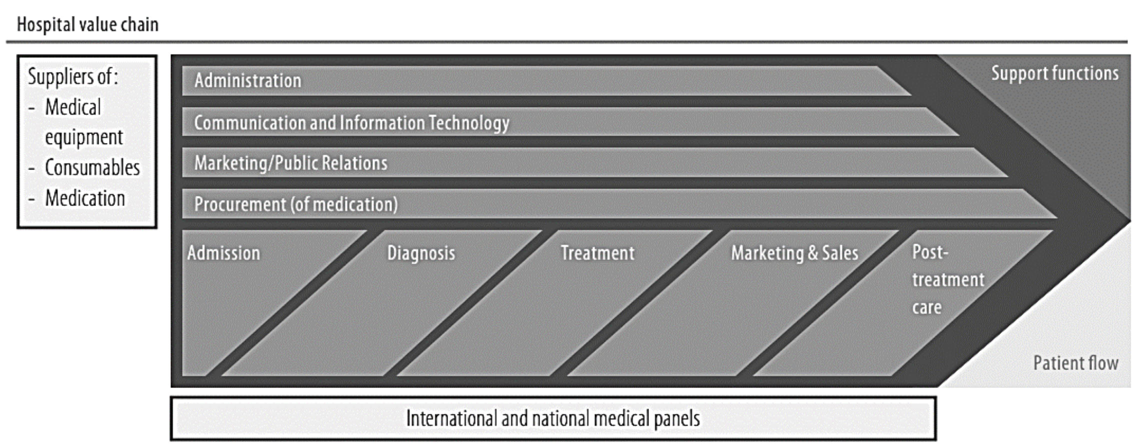


Fig. 113 The value chain of a hospital (ISO, 2011, p. 15)

[48] ICD-11 codes were released on June 2018 (World Health Organization, 2018). Suggestions in this chapter shall be adapted to the new codes.

7.4 Data analysis

Data analysis in this section follows the same method as presented in Chapter 5. The rest of the section is elaborated based on each root concept in EBD theory (Section 5.4.1.1 to 5.4.1.5). Each root concept in EBD theory is complemented with the respective concepts in the proposed core ontology. Section 6.4.1.6 ends with a discussion about the findings in data analysis.

7.4.1.1 Natural environment

The natural environment refers to all the [natural] laws in a product's working environment (Zeng, 2004a, 2015). Concepts in the proposed core ontology related to the natural environment are summarized in Table 35.

Table 60 Natural environment and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Natural environment	Environment	Organs, blood, mental and behavioral disorders, metabolic diseases, circulatory system, etc.
	Interaction	Interactions, interaction of all these components, interaction of all these stakeholders, etc.
	Risk	Financial risk, health risk, risk factors to health
	Safety	ICD 10 Coding, ICD-11 codes, injury, poisoning, physical and mental health, etc.
	State	Health status (e.g., life expectancy and mortality), status quo
	Validation	Improvement in health and well-being, value for money
	Verification	Appropriateness, acceptability, accessibility, competence, continuity, effectiveness, safety, etc.

7.4.1.2 Built environment

The built environments are the artefacts designed and created by human beings (e.g., man-made devices) (Zeng, 2004a, 2015). Concepts in the proposed core ontology related to the built environment are summarized in Table 36.

Table 61 Built environment and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Built environment	Architecture	Framework, components, conceptual drawing
	Attribute	Characteristic, indicators, utilization, cost, etc.
	Availability	Availability, available resources, availability of the network, bandwidth availability, available clinical data, etc.
	Baseline	Health status, well-being, status quo, disparities reports, etc.
	Concept of operations	Strategic plan, health status, leadership and governance, health system resources, etc.
	Concern	World health, health coverage, social and environmental determinants, universal access policy, get full cash contribution from the government, statutory regulations, confidentiality, privacy, security of data, etc.
	Document	Best practices, (electronic health) record, electronic medical record, referrals, prescription, etc.
	Enabling system	Health centers, hospitals, clinics, home care, research networks, scientific knowledge, electronic health technologies, etc.
	Flexibility	Home telehealth, electronic health technologies, home care, etc.
	Functional requirement	Access to information and data, scientific knowledge, research networks, people (patients, consumers, providers, purchasers, practitioners, policy makers, general authorities and educators), social security, private-public partnerships, health insurance more affordable, technologies (e.g., information systems), facilities, equipment, methods, best practices, healthcare outcomes, cost, utilization, and quality (safety, effectiveness, efficiency, and competency), etc.
	Interface	Human-computer interface
	Issue	Isolated databases, usability issues, inconsistent interoperability standards, culture of health care, complexity of health care

		including multiple chronic diseases, treatments and technologies available, etc.
	Need	Human needs, needs of a healthcare delivery system, needs of the patient, needs of the caregiver, need for the reduction in time associated with patient care, etc.
	Operational concept	Act, regulations, policies: public administration, comprehensiveness, universality, portability, and accessibility; etc.
	Port	Hospital [flow of information (diagnostic) and matter (treatment)], clinic, home, electronic health technologies, etc.
	Product	Best practice, medical devices, treatment, drug therapies, method, supplies, pharmaceutical, diagnostic, record, etc.
	Project	OECD Health Care Quality Indicators project
	Quality	Quality (safety, effectiveness, efficiency, and competency), high-quality health services, healthcare research and quality, etc.
	Reliability	Responsiveness, transparency, preventive, etc.
	Requirement	Original requirements, bandwidth requirements, design requirements, etc.
	Resource	Health workforce, supplies, laboratories, facilities, equipment, research networks, etc.
	Service	Health services, medical services, etc.
	Stakeholder requirement	Access to care (primary and preventive)
	Standard	Health care data standards, data interchange formats, terminologies, knowledge representations, protocol, structural and semantic standards (vocabularies, code, and value set), etc.
	System	Health system, nervous system, circulatory system, respiratory system, digestive system, musculoskeletal system, genitourinary system, etc.

	System element	Nursing, laboratory, drugs, operating room and other facilities, equipment, supplies, physician, health care data standards and technical infrastructure, core clinical applications, information/communication systems, etc.
	System requirement	Patient safety, person and family centered care, care coordination, effective treatment, healthy living, care affordability, priority populations, etc.
	System-of-interest	Health systems
	Trade-off	Value for money, usability and security, best care at lower cost, etc.

7.4.1.3 Human environment

The human environments include all the human beings but particularly the human users of an artifact (Zeng, 2015). Concepts in the proposed core ontology related to the human environment are summarized in Table 37.

Table 62 Human environment and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Human environment	Acquirer	Policy makers, patient, purchasers, providers, etc.
	Customer	Patients, educators, general population, etc.
	Operator	Patient, physicians, Government, health industry, World Health Organization, etc.
	Organization	Government (e.g., federal and provincial), OECD, World Health organization, Health Canada, Canadian Academy of Health Sciences, Canadian Institute for Health Information, Canada Health Infoway, etc.
	Party	Overall society (population), general authorities, consumers, providers, purchasers, practitioners, policy makers, educators, etc.

	Stakeholder	Patients, consumers, providers, purchasers, practitioners, policy makers, general authorities and educators
	Supplier	Providers, health industry, Government, Public/public groups, etc.
	User	Patient, physicians, public, etc.

7.4.1.4 Design process

The design process are the activities (i.e., environment analysis, conflict identification, and solution generation) executed to change an existing environment to a desired one by creating a new artifact into the existing one (Zeng, 2015). Concepts in the proposed core ontology related to the design process are summarized in Table 38.

Table 63 Design process and PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Design process	Activity	Health care activities
	Process	Decision making process, consultation process, processes of care, healthcare delivery processes, process for a national clinical assessment program, process to principles of consistency, efficiency, objectivity, responsiveness, and transparency, etc.
	Quality management	OECD Health Care Quality Indicators, national quality strategy, etc.

7.4.1.5 Life cycle

Life cycle are phases (stages) occurring in the life of a product (e.g., design, manufacturing, sales, transportation, use, maintenance, and recycle) (Z. Chen & Zeng, 2006). Concepts in the proposed core ontology related to the life cycle are summarized in Table 39.

Table 64 Life cycle and the PCO as coding scheme

EBD root concepts	Concepts in PCO	Instance
Life cycle	Life cycle	Life cycle of healthcare, life cycle of care
	Life cycle model	Value chain, roadmap
	Stage	See system life cycle processes
	System life cycle processes	Admission, diagnosis, treatment, marketing & sales, and post-treatment care [at hospital level]

7.4.1.6 Discussion

Data analysis proves that the concepts in the proposed core ontology are valid and necessary to represent the domain of designing the right framework for healthcare decision support. Evidence of proof is summarized for EBD root concepts and concepts in the proposed core ontology from Table 35 to Table 39. Therefore, each concept is valid and needed to communicate and understand healthcare decision support. As a result, the proposed core ontology can be interpreted a valid minimum information model to communicate and understand the context of healthcare decision support.

In general, the subjective method of characterization enables to allocate the same concepts in more than one concept in the proposed core ontology. This observation was also found and discussed in data analysis in Chapter 5 and Chapter 6.

7.5 Conclusions

In this chapter, essential attributes of a good framework for healthcare decisions were analyzed. This analysis involves the study of the existing situations in both United States and Canada. The analysis indicates that the solutions presented in the case study are not specific to a particular country. The authors have attempted to analyze healthcare decision making from a global perspective. Additionally, as indicated before, healthcare decision making involves individuals from different backgrounds and expertise. While describing the problems and solutions from a software engineering perspective the authors have perceived the multi-dimensional nature of healthcare decision support. This case study provides a basis for developing software prototypes that can bridge some of the existing gaps in healthcare decision support.

The case study proves that EBD root concepts and the concepts in the proposed core ontology are effective to communicate and understand healthcare decision support, subsequently the broad context of requirements in this kind of engineering projects. All these concepts are implicit in engineering communication during the design of healthcare decision support. Hence, the concepts conform a common vocabulary during healthcare decision support. These concepts will increase the likelihood to improve communication and understanding during healthcare decision support design. So, the proposed core ontology can be interpreted as a valid minimum information model to communicate and understand the context of healthcare decision support.

There are limitations in data analysis. One limitation is that the characterization of concepts was not exhaustive. Exhaustive characterization of the concepts may help to interpret the relative importance of each concept. The relative importance of each concept provides guidance about where to prioritize more attention while communicating and understanding requirements about healthcare decision support. At the current stage of development of the ontology, it was considered more important to identify the right concepts than identifying their relative importance. The right concepts shall be understood properly before trying to understand their relative importance. Future work may involve defining the relative importance of each concept. In addition, future work needs to investigate specific system life cycle analyses and communication mechanism during healthcare decision support projects. Finally, future work can also try to tackle the identified problems in characterization discussed in Section 6.4.1.6.

Chapter 8: Conclusions and future work

This section presents conclusions, limitations, and future work. Conclusions (Section 8.1) summarize research achievements and their rational. Limitations (Section 8.2) state current limits in the stage of development of the proposed core ontology. The section also associates the limits to the given rational and general future work intentions to overcome the limits. Finally, future work (Section 8.3) associates the stated limitations to specific topics depicting possible research paths.

8.1 Conclusions

Economies prosper by designing and manufacturing a variety of innovative products (Industry Canada, 2007, 2010, 2012; World Economic Forum, 2017, p. 319). Requirements are fundamental aspect in designing all products including innovative products. Challenges associated to poor communication (i.e., lack of common vocabulary) has hampered understanding in the context of requirements causing poor quality, cost overruns, and late deliveries in designing innovative products. Theories and models have been proposed in the past to address this challenge, but they have not been effective until now. A new means to solve the challenge is through ontologies. The main idea to solve the challenge through ontologies is defined in Fig. 8.

Effective communication requires a common vocabulary. An ontology provides a description of the terminology, concepts and relationships for a particular area of interest. An ontology may be viewed as a declarative encoding of the meaning of the domain vocabulary terms, thus making it a key to enabling communication. For systems that are used by people whose understanding of a domain is not necessarily consistent, an explicit description of the important terms can be extremely useful.

Fig. 114 An introduction to knowledge representation and ontology development for systems engineers (Kendell & Jenkins, 2010)

After identifying the problem of requirements in designing innovative products, the context of requirements was investigated. This investigation included 7 topic areas: 1) ontology, 2) natural environment, 3) human environment, 4) built environment, 5) life cycle, 6) design process, and 7) requirements. The origin of the areas was based on the objective of this thesis (i.e., “to propose a requirements ontology to guide the analysis of systems life cycle processes") and guidance from EBD theory (Zeng, 2015). The topic areas and review enable to explore and understand the context of requirements. During the review, it was realized that the context of requirements is a complex domain of research. Complexity arises from the huge scope and variety of knowledge needed to acquire, interpret, integrate, and trace information. In addition, it is important to point out the complexity that many details about requirements and design are confidential.

After investigating and gaining knowledge about the context of requirements and design, the research methodology was formulated. From philosophical point of view, ontologies relate to theories, models, and research methodologies. To integrate all these concepts into a research methodology, foundations from EBD theory were adopted. EBD theory helped to organize and interpret the context of the ontology. From philosophical point of view, ontologies enable to express theories, theories enable to derive models, and models enable to define methodologies[49]; for instance refer to Chakrabarti and Blessing (2016, pp. 14-15). Although the proposed ontology was rooted in EBD theory, case studies were conducted before the creation of the ontology. The case studies, as part of the research methodology, enable to partially validate inductively the ontology based on retrospection. Implicitly the root concepts of EBD theory also enable to partially validate deductively the ontology. The remaining validation was based on document analysis (i.e., publications from international research groups and international standards). The documents enable to identify the right/shared semantics (i.e., concepts and relationships) in the domain of the ontology. The concepts and relationships were integrated into a proposed core ontology. Lightest versions of the proposed core ontology were also created based on concepts relative frequency analysis. The proposed core ontology comply with the design research methodology framework at this stage of research proposed by Blessing and Chakrabarti (2009, p. 39).

The context of requirements and design was framed through case studies. Case studies[50] were conducted with two purposes: enable validation and make explicit major concepts in the ontology. The case studies proved that the concepts in the ontology appear in the three different investigated knowledge domains (i.e., quality & area development planning, learning & aircraft design, and decision support in healthcare systems). The case studies are sources of content independent from the ones used during the ontology design process. Therefore, the case studies trigger to think that

[49] Ontologies → theories → models → methodologies.
[50] Also some parts of the literature review.

the proposed core ontology is also applicable to other innovative products. Such thinking also enables to consider at this stage of development that the proposed core ontology is a valid minimum information model (i.e., domain of discourse and specific content). The proposed core ontology shall be investigated to create specific shared mental models (Toche et al., 2010) and communication mechanisms (Hisarciklilar, Sheikh, Yadav, & Thomson, 2013; Klapsis & Thomson, 1996, 1997; Suss & Thomson, 2009) that exist in requirements and design.

The context of requirements and design affects different aspects of design competency and learning. From design competency and learning point of view, EBD theory supported metacognitive skills (University of Waterloo: Center for teaching excellence, 2018) in research formulation and EBD methodology guided data collection (i.e., knowledge acquisition, recording, and integration) in the three case studies. Research formulation and execution (e.g., case studies) put to the limits information processing skills especially for me as a novice assistant researcher in training. Each case study led me to investigate new domains of knowledge respect to my knowledge baseline at the starting each project. Having EBD helped me to be aware of what was needed (EBD theory), what was missing (EBD theory), and how to proceed (EBD methodology) during the case studies. Therefore, a perceived unstructured problem was formulated into a structured one based on EBD. In the same line of reasoning as for EBD, the proposed ontology may help to create an initial context to identify proactively unforeseen problems. Data analysis in the case studies makes explicit initial attempts of how the proposed core ontology can support EBD either at the individual designer level or multidisciplinary teams with even an extended structured guidance in the context of requirements and design.

8.2 Limitations

The proposed core ontology was created based on the author's knowledge gained during the literature review, case studies, document analysis, and discussions. The proposed ontology still needs to be verified and validated by the systems engineering, design community, and other intended users. It is important to highlight that each case study conducted in this research for data analysis was not exhaustive. An exhaustive data analysis shall allocate all the statements in data collection into the concepts in the proposed core ontology. Considering a balance between the amounts of resources (knowledge and time) needed to perform an exhaustive data analysis, the author reflected in the "shared" characteristic of a good ontology. Based on this characteristic, two beliefs set the reference to stop at this stage of development of the ontology. First, it is believed that the proposed core ontology needs to be verified and validated by the previous communities and intended users before moving forward to an exhaustive data analysis. Second, each case study acknowledged difficulties in characterizing each concept in the ontology. As a result, the author thought that the current stage of the ontology is internally valid, but it needs to acquire feedback from the communities. This feedback may also enable to build a shared thesaurus of terms and ontological definitions. Specific methods to create this information products need to be investigated.

Considering that the ontology was created based on the author's knowledge, the proposed ontology may have semantic errors. These errors need to be identified and corrected. However, access to knowledge and intellectual resources are foreseen as a challenge.

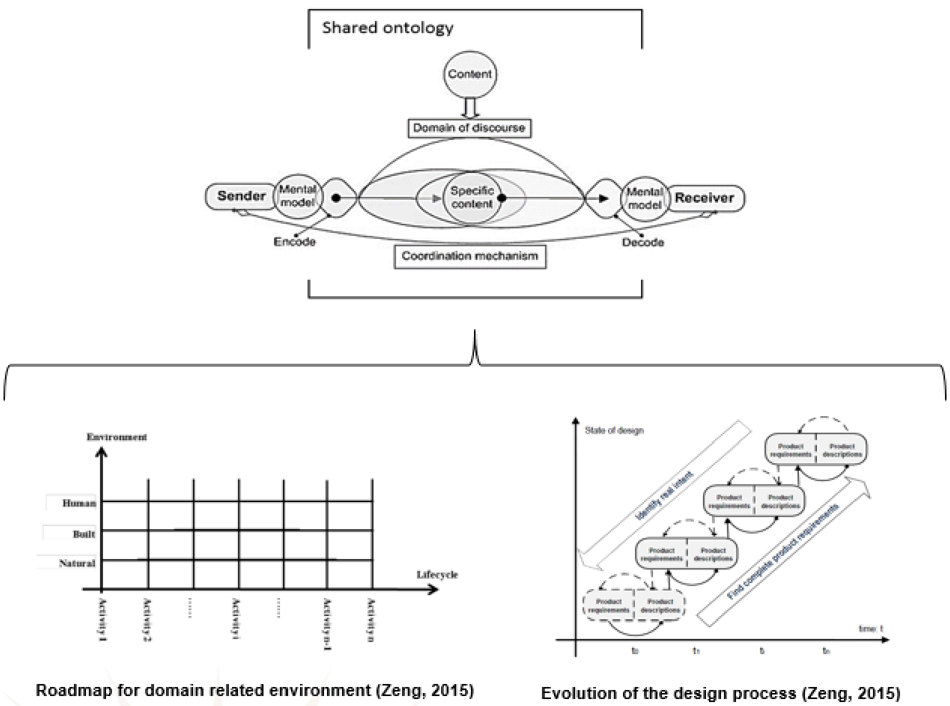


Fig. 115 Ontology enabled EBD methodology

In addition, the ontology needs to be piloted in small projects in order to validate it for specific use cases and more detail descriptions. As a result, descriptive and prescriptive work related to the ontology still needs to be investigated. Descriptive and prescriptive work shall cover specific support. In fact, specific support can be conceptualized in terms of EBD methodology as illustrated in Fig. 115. Specific support for system life cycle analysis support may include: 1) deployment analysis, 2) design analysis, 3) electromagnetic compatibility and radio frequency management analysis, 4) environmental impact analysis, 5) human systems engineering and analysis, 6) life cycle cost analysis, 7) manufacturing and producibility analysis, 8) mission operation analysis, 9) reliability, maintainability and availability analysis, 10) safety and health hazard analysis, 11) supportability, and integration logistics support analysis, 12) survivability analysis, 13) system cost/effectiveness analysis, 14) system modeling, 15) system security analysis, 16) trades studies, 17) training analysis, and 18) disposal analysis (INCOSE, 2004, pp. 154-178). These analyses are sometimes known as ilities or specialty engineering (INCOSE, 2015, pp. 211-241). Specific support to the analyses may enable to identify and create new specific ontologies that shall be an extension to the proposed core ontology. From requirements engineering perspective, specific support can be created to implement the international standard (ISO/IEC/IEEE, 2011) aligned with the international standard (ISO/IEC/IEEE, 2015). An alternative approach could be to create specific support to implement the requirement process in Fig. 116 considering the proposed ontology. This requirement process could also be investigated and enabled through the ontology in the context of the international standards.

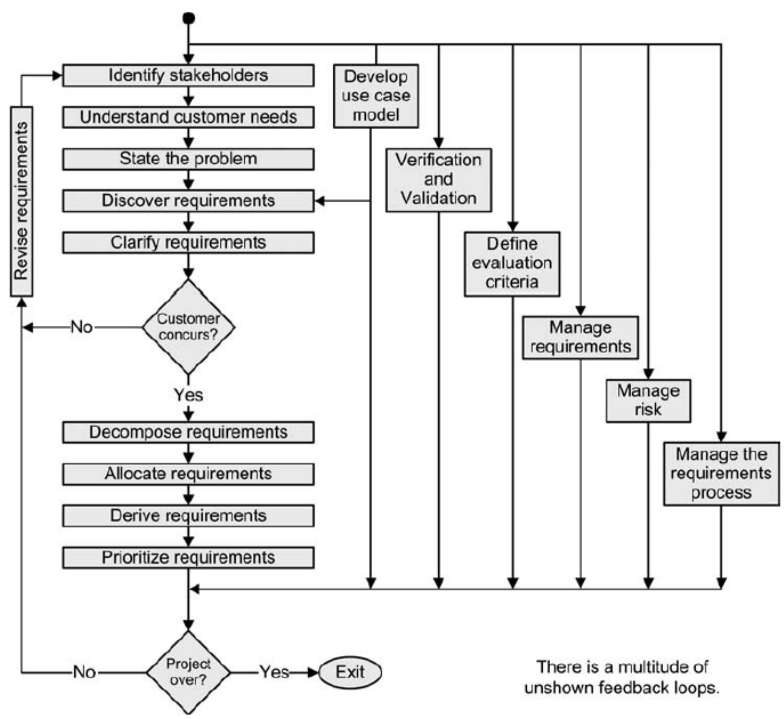


Fig. 116 The requirement process (Bahill & Dean, 2009)

From ontology language point of view, the created ontology can be defined as approaching the most formal way of representation (e.g., first-order logic). Therefore, more formality can be obtained if the ontology is expressed in formal languages. At this point, this limitation was not addressed as it was assumed that higher degree of formality may reduce transferability to a wider audience. That is the reason to use ROM enabled natural language representation (i.e., written English) to express the ontology. However, automation support shall be investigated using ROM and formal languages (e.g., first-order logic or ATDM).

Finally, the presented ontology does not claim to solve the existing challenges in requirements, but the proposed ontology can be claimed as a step forward to formalize the context of requirements[51]. This formalization is the base to improve communication and understanding, which eventually can help to reduce poor quality, cost overruns, and late deliveries. The formalization can also serve as a baseline to critique and create a common vocabulary (e.g., shared ontology) in the context of requirements and design. All designs start with an initial attempt with low fidelity, but the formalization can be the base to investigate computational tools based on the ontology, and to facilitate learning and knowledge transfer.

8.3 Future work

Future work corresponds to address the found limitations. Future work can be summarized in the following topics: 1) shared ontology and related information products, 2) computational tools (e.g., automated reasoning), 3) communication mechanism, 4) facilitation of learning and knowledge transfer, and 5) specific support.

[51] The beginning of wisdom is the definition of terms – attributed to Socrates (National Research Council, 2014, p. 1).

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Appendix A: Ontology design process – identifying existing taxonomies & comparison – extending step 8.2

A.1 Introduction

This appendix expands step 8.2 in Chapter 4. This step concerns with identifying existing taxonomies. This expansion is needed to record data collected about existing taxonomies. Existing taxonomies come from three different European research efforts in the context of the investigated ontology in this thesis. The existing taxonomies are discussed in Section A.2. After identifying the taxonomies, they are compared in Section A.3. The result of the comparison leads to conclude that the identified taxonomies are complementary. Considering that the identified taxonomies are complementary, Section A.4 consolidates and integrates the identified taxonomies. This consolidation ends with specific lists of concepts and relationships to continue step 8.3 in Chapter 4.

A.2 Step 8.2: Identify existing taxonomies

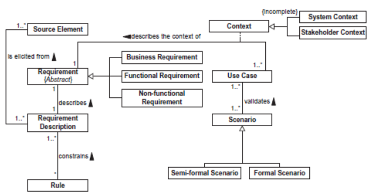
A taxonomy is a scheme that partitions a body of knowledge and defines the relationships among the pieces (ISO/IEC/IEEE, 2017). Researchers have attempted to create taxonomies in the context of requirements investigated under the subject of requirements ontology for system life cycle processes. For the context of this research, taxonomies and ontologies have equal semantic meaning (van Rees, 2003). This review is not exhaustive, but three major ontologies are presented, discussed, and evaluated in this section. The ontologies have been created in Europe by two research groups and a single researcher. Each of the ontologies is introduced from Section A.2.1 to Section A.2.3 respectively.

A.2.1 COMPASS research project

The first research group has proposed different ontologies for both the complete context of MBSE (model-based systems engineering) and a specific requirement ontology under the COMPASS research project (COMPASS Club, 2014). The complete effort of these researchers can be categorized into the following groups: 1) model-based requirements ontology (Section A.2.1.1), 2) MBSE ontology (Section A.2.1.2), and 3) alternative MBSE ontology (Section A.2.1.3). In addition, this section compares the two MBSE ontologies (Section A.2.1.4), presents a summary of concepts (Section A.2.1.5), and define relationships from the proposed ontologies (Section A.2.1.6).

A.2.1.1 Model-based requirements engineering ontology

Holt, Perry, and Brownsword (2011, p. 96) created the model-based requirement engineering ontology in Fig. 117. The ontology consists of key concepts such as source element, requirement, requirement description, rules, types of requirements (i.e., business, functional, and non-functional), context, use case, and scenario. The ontology relates the concepts using abstract relationships in SysML such as association (arrows with no head), and generalization/specialization (arrows with heads) (Holt et al., 2011, pp. 37, 40-41, 54). SysML relationships are complemented with the use of multiplicities (i.e., 1..*, *, and 1) to express cardinality within the ontology (Holt et al., 2011, p. 38). Recent work by Holt et al. (2012) and Holt et al. (2015) adapt the ontology from system level to the context of systems of systems (SoS). The requirement ontology serves as a basis for different views of the context to visualize a complete set of requirements (Holt et al., 2015). Holt et al. (2015) call this approach ACRE, which stands for *"Approach to Context-based Requirements Engineering"*. For example, Holt et al. (2015) use the ontology in Fig. 117 to propose the SoS-ACRE ontology in Fig. 118, where the latter shows minor variations in the main concepts. After, the SoS-ACRE ontology is used to propose the SoS-ACRE framework in Fig. 119, which presents different view of the context of requirements. The views are generated based on requirements processes such as shown in Fig. 120. Describing the processes in Fig. 120 are beyond the scope of this research; however, the authors define them in the this report (Perry & Holt, 2012). The processes in Fig. 120 are related to processes suggested in standards such as ISO/IEC/IEEE (2015) and ISO/IEC/IEEE (2011). Fig. 118, Fig. 119, and Fig. 120 can be interpreted as vocabulary, outcomes, and procedural aspect respectively; where the latter maps/applies the vocabulary to obtain the desired outcomes in different views. Fig. 118, Fig. 119, and Fig. 120 which originated from Fig. 117 conforms what is called the SoS-ACRE approach. Major differences are in the expansion of the blocks called requirement and context inheritances between Fig. 117 to Fig. 118. These expansions lead to the refinements of Fig. 119, and Fig. 120. The SoS-ACRE approach is composed of 60 concepts: 46 new concepts (defined from Fig. 117 to Fig. 120), and 14 repeating concepts. The repeating concepts and their distribution are: use case (2), rule (2), source element (2), requirement (1), scenario (1), formal scenario (1), semi-formal scenario (1), context (1), system context (1), stakeholder context (1), and need (1). The function of repeating concepts is to link the different diagrams from Fig. 117 to Fig. 120. The links enable integration of small diagrams into one ontology.



Concepts	Sum of concepts
Source element, Requirement, Requirement description, Rule, Business requirement, Functional requirement, Non-functional requirement, Context, System context, Stakeholder context, Use case, Scenario, Semi-formal scenario, Formal scenario	14

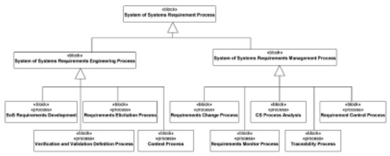
Fig. 117 Model-based requirements engineering ontology, constructed from Holt et al. (2011, p. 96)

Concepts	Sum of concepts
Need, Goal, Capability, System, Constituent system, System of systems, Virtual, Acknowledged, Collaborative, Directed	10

Fig. 118 SoS-ACRE ontology. constructed from Holt et al. (2015)

Concepts	Sum of concepts
Validation interaction view, Context definition view, Context interaction view, Requirement context view, Stakeholder, Validation view, Analysis relationship, Requirement description view, Definition rule set view, Source element view	10

Fig. 119 SoS-ACRE framework, constructed from Holt et al. (2015)

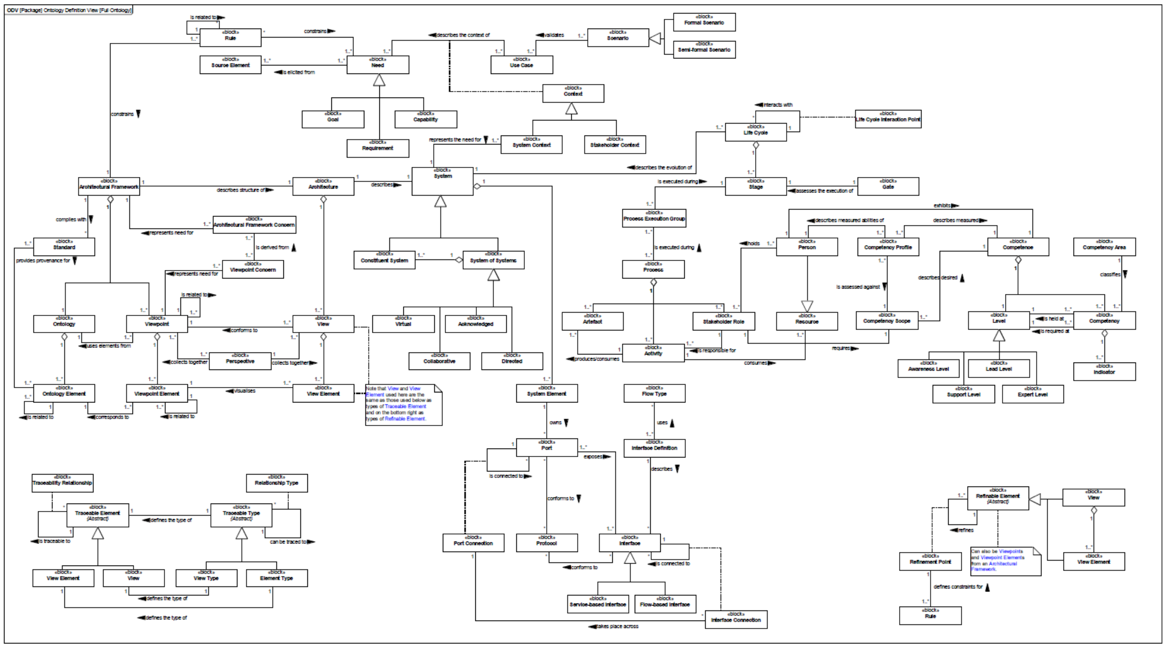


Concepts	Sum of concepts
System of systems requirement process, System of systems requirements engineering process, System of systems requirements management process, SoS requirements development, Verification and validation definition process, Requirements elicitation process, Context process, Requirements change process, Requirements monitor process, CS process analysis, Traceability process, Requirement control process	12

Fig. 120 SoS-ACRE requirements processes, constructed from Holt et al. (2015)

A.2.1.2 MBSE ontology

After such achievement in MBSE and ontologies, the group of researchers have proposed two MSBE ontologies. One of the ontologies is called the full COMPASS SoSE ontology, where COMPASS stands for *Comprehensive Modelling for Advanced Systems of Systems*, and SoSE stands for *System of systems engineering* (Perry, 2014). The ontology is presented in Fig. 121. The ontology is composed of 77 concepts (called blocks); however, 5 of them are repeating. The repeating concepts and their respective distribution are as follows: view (2), view element (2), and rule (1). The repeating concepts are located in the portions (bottom left and right) of the figure that seems unconnected to the larger body of the figure. The repetition happens to relate those portions to the larger ontology in the figure. Besides the block, the figure also presents three kinds of relationships from SysML, i.e., generalization/specialization, aggregations, and associations; where relationships are complemented with multiplicities. The relationships define connections between concepts. The figure also includes two notes to clarify the use of concepts where the notes are associated. The COMPASS SoSE ontology in the figure integrates six separate ontologies (i.e., SoS requirements, process and competency, architectures and architectural frameworks, SoS integration, traceability, and refinement) (Perry, 2014, pp. 17, 158-161). Defining the complete COMPASS SoSE ontology is beyond the scope of this thesis; however, interested readers can refer to the original source (Perry, 2014). Perry (2014, pp. 145-149) also defines each of the concepts in the ontology.

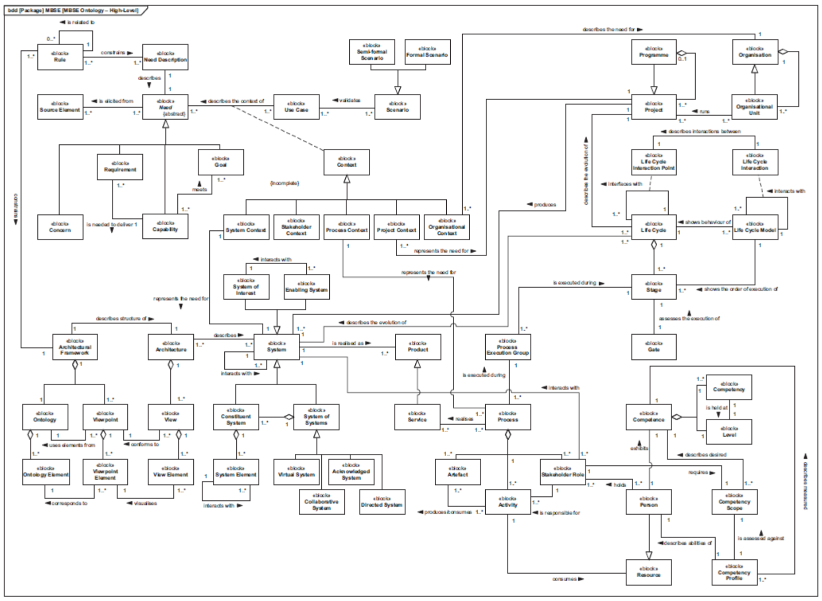


Concepts	Sum of concepts
Acknowledged, Activity, Architectural framework, Architectural framework concern, Architecture, Artefact, Awareness level, Capability Collaborative, Competence, Competency, Competency area, Competency profile, Competency scope, Constituent system, Context, Directed, Element type, Expert level, Flow type, Flow-based interface, Formal scenario, Gate, Goal, Indicator, Interface, Interface connection, Interface definition, Lead level, Level, Life cycle, Life cycle interaction point, Need, Ontology, Ontology element, Person, Perspective, Port, Port connection, Process, Process execution group, Protocol, Refinable element, Refinement point, Relationship type, Requirement, Resource, Rule, Scenario, Semi-formal scenario, Service-based interface, Source element, Stage, Stakeholder context, Stakeholder role, Standard, Support level, System, System context, System element, System of systems, Traceability relationship, Traceable element, Traceable type, Use case, View, View element, View type, Viewpoint, Viewpoint concern, Viewpoint element, Virtual	72

Fig. 121 The full COMPASS SoSE ontology, constructed from Perry (2014, p. 18)

A.2.1.3 Alternative MBSE ontology

Besides the COMPASS SoSE ontology, Holt, Perry, and Brownsword (2016) proposed an alternative ontology for MBSE. The authors call the ontology the full MBSE ontology, see Fig. 122. The ontology is composed of 60 concepts (called blocks). Relationships between concepts in Fig. 122 are read and interpreted as previously discussed for Fig. 121.



Concepts	Sum of concepts
Acknowledged system, Activity, Architectural framework, Architecture, Artefact, Capability, Collaborative system, Competence, Competency, Competency profile, Competency scope, Concern, Constituent system, Context, Directed system, Enabling system, Formal scenario, Gate, Goal, Level, Life cycle, Life cycle interaction, Life cycle interaction point, Life cycle model, Need, Need description, Ontology, Ontology element, Organization, Organizational context, Organizational unit, Person, Process, Process context, Process execution group, Product, Program, Project, Project context, Requirement, Resource, Rule, Scenario, Semi-formal scenario, Service, Source element, Stage, Stakeholder context, Stakeholder role, System, System context, System element, System of interest, System of systems, Use case, View, View element, Viewpoint, Viewpoint element, Virtual system	60

Fig. 122 The full MBSE ontology, constructed from Holt et al. (2016, p. 368)

A.2.1.4 Comparing MBSE ontology and the alternative MBSE

Both MBSE ontologies in Fig. 121 and Fig. 122 have overlapping and complementary concepts. If the ontologies in both figures are combined, they have together 88 concepts. There are 28 concepts included in the ontology in Fig. 121 not included in Fig. 122. The concepts are: 1) architectural framework concern, 2) architecture, 3) awareness level, 4) competency area, 5) element type, 6) expert level, 7) flow type, 8) flow-based interface, 9) indicator, 10) interface, 11) interface connection, 12) interface definition, 13) lead level, 14) perspective, 15) port, 16) port connection, 17) protocol, 18) refinement element, 19) refinement point, 20) relationship type, 21) service-based interface, 22) standard, 23) support level, 24) traceability relationship, 25) traceable element, 26) traceable type, 27) view type, and 28) viewpoint concern. If these 28 concepts are added to the 60 concepts in Fig. 122, the total 88 concepts are obtained. There are 16 concepts included in the ontology in Fig. 122 not included in Fig. 121. The concepts are: 1) architecture, 2) concern, 3) enabling system, 4) life cycle interaction, 5) life cycle model, 6) need description, 7) organization, 8) organizational context, 9) organizational unit, 10) process context, 11) product, 12) program, 13) project, 14) project context, 15) service, and 16) system of interest. If these 16 concepts are added to the 72 concepts in Fig. 121, the total 88 concepts are obtained. Both figures share 44 core concepts: 1) acknowledge system, 2) activity, 3) architectural framework, 4) artefact, 5) capability, 6) collaborative system, 7) competence, 8) competency, 9) competency profile, 10) competency scope, 11) constituent system, 12) context, 13) directed system, 14) formal scenario, 15) gate, 16) goal, 17) level, 18) life cycle, 19) life cycle interaction point, 20) need, 21) ontology, 22) ontology element, 23) person, 24) process, 25) process execution group, 26) requirement, 27) resource, 28) rule, 29) scenario, 30) semi-formal scenario, 31) source element, 32) stage, 33) stakeholder context, 34) stakeholder role, 35) system, 36) system context, 37) system element, 38) system of system, 39) use case, 40) view, 41) view element, 42) viewpoint, 43) viewpoint element, and 44) virtual system. The ontologies have 4 concepts (i.e., acknowledged system, collaborative system, directed system, and virtual system) that are employed as synonyms and belong to the core concepts. The concepts in the ontologies also keep the core of the model-based requirements engineering ontology in Fig. 117. Although the ontologies presented from this research group have reached significant achievement, there are opportunities to improve the domain of requirements. In addition, opportunities exist to apply and understand the ontology in specific cases.

A.2.1.5 Concepts: summary

As defined in Section A.2.1.5, Fig. 121 and Fig. 122 have together 88 concepts. These concepts also overlap and complement with the concepts defined from Fig. 117 to Fig. 120. The total number of concepts defined in the 6 figures are 192. From the 192 concepts, 114 concepts are unique, 4 concepts (i.e., acknowledged system & acknowledge, collaborative system & collaborative, directed system & directed, and virtual system & virtual) are synonyms, and 74 concepts are repeating. The repeating 74 concepts are connecting concepts needed to integrate the information models into one ontology. Fig. 117 to Fig. 120 complement 26 concepts to the 88 unique concepts from Fig. 121 and Fig. 122. Thus, the 114 unique concepts are summarized in Table 65.

Table 65 COMPASS research group and their unique concepts

Group	Concepts
COMPASS research group	Acknowledged system, Activity, Analysis relationship, Architectural framework, Architectural framework concern, Architecture, Artefact, Awareness level, Business requirement, Capability, Collaborative system, Competence, Competence, Competency, Competency area, Competency profile, Competency scope, Concern, Constituent system, Context, Context definition view, Context interaction view, Context process, CS process analysis, Definition rule set view, Directed system, Element type, Enabling system, Expert level, Flow type, Flow-based interface, Formal scenario, Functional requirement, Gate, Goal, Indicator, Interface, Interface connection, Interface definition, Lead level, Level, Life cycle, Life cycle interaction, Life cycle interaction point, Life cycle model, Need, Need description, Non-functional requirement, Ontology, Ontology element, Organization, Organizational context, Organizational unit, Person, Perspective, Port, Port connection, Process, Process context, Process execution group, Product, Program, Project, Project context, Protocol, Refinable element, Refinement point, Relationship type, Requirement, Requirement context view, Requirement control process, Requirement description, Requirement

	description view, Requirements change process, Requirements elicitation process, Requirements monitor process, Resource, Rule, Scenario, Semi-formal scenario, Service, Service-based interface, SoS requirements development, Source element, Source element view, Stage, Stakeholder, Stakeholder context, Stakeholder role, Standard, Support level, System, System context, System element, System of interest, System of systems, System of systems requirement process, System of systems requirements engineering process, System of systems requirements management process, Traceability process, Traceability relationship, Traceable element, Traceable type, Use case, Validation interaction view, Validation view, Verification and validation definition process, View, View element, View type, Viewpoint, Viewpoint concern, Viewpoint element, Virtual system

A.2.1.6 Relationships

Besides concepts, ontologies are also composed of relationships to connect these concepts. Fig. 117 to Fig. 122 show different kinds of relationships. The relationships can be categorized as multiplicities, generic, and specific associations (i.e., a special case of a generic relationship). Table 66 defines the different types of multiplicities that appear from Fig. 117 to Fig. 122. Table 67 defines the generic type of relationships that appear from Fig. 117 to Fig. 122. Generic types of relationships correspond to the types of abstract relationships defined in the literature review section for SysML. The association relationship in Table 67 supports a variable called verb phrase. Therefore, the variables need to be defined to form specific case (aka instances of associations). In total, the research group defines 121 instances of associations. From the 121 instances, 59 instances conform unique instances of association, while the remaining 62 are repeating 30 instances from the 59 unique instances. The unique 59 instances of associations are defined in Table 68. The repeating 30 instances and their relative frequency can be inferred from the same table, which are defined by the values greater than 1 in the column titled sum.

Table 66 Type of multiplicities and how to read them, constructed from Holt et al. (2011, p. 38)

Multiplicity	Read as
1 OR 1..1 OR empty	Each
1..*	One or more
0..1	Zero or one
* OR 0..*	Zero or more

Table 67 Type of generic relationships, how to read them, and notation; constructed from Holt et al. (2011, pp. 36-43, 52-56, 301-310)

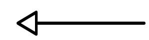
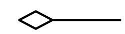
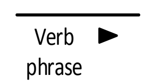
Generic relationship	Read as	Notation
Generalization / specialization	Has type / is type of	
Aggregation	Is made of up	
Association	Read as following the defined phrase on the relationship	
Dependency	Is some kind of (unspecified) relationship / to be interpreted on a case by case basis	

Table 68 Instances of association and their source by the COMPASS research group

#	Instance of association	Fig. 117	Fig. 118	Fig. 119	Fig. 120	Fig. 121	Fig. 122	Sum
1	constrains	1	1	1	2	N/A	2	7
2	represents the need for	0	1	0	3	N/A	3	7
3	interacts with	0	0	0	5	N/A	1	6
4	describes	1	0	0	2	N/A	2	5
5	is elicited from	1	1	1	1	N/A	1	5
6	is related to	0	0	0	1	N/A	4	5
7	validates	1	1	1	1	N/A	1	5
8	conforms to	0	0	0	1	N/A	3	4
9	is executed during	0	0	0	2	N/A	2	4
10	defines the type of	0	0	0	0	N/A	3	3

11	describes the evolution of	0	0	0	2	N/A	1	3
12	assesses the execution of	0	0	0	1	N/A	1	2
13	collects together	0	0	0	0	N/A	2	2
14	combines	0	0	2	0	N/A	0	2
15	consumes	0	0	0	1	N/A	1	2
16	corresponds to	0	0	0	1	N/A	1	2
17	describes desired	0	0	0	1	N/A	1	2
18	describes measured	0	0	0	1	N/A	1	2
19	describes structure of	0	0	0	1	N/A	1	2
20	describes the context of	0	0	0	1	N/A	1	2
21	describes the context of	1	1	0	0	N/A	0	2
22	exhibits	0	0	0	1	N/A	1	2
23	is assessed against	0	0	0	1	N/A	1	2
24	is connected to	0	0	0	0	N/A	2	2
25	is held at	0	0	0	1	N/A	1	2
26	is responsible for	0	0	0	1	N/A	1	2
27	produces/consumes	0	0	0	1	N/A	1	2
28	requires	0	0	0	1	N/A	1	2
29	uses elements from	0	0	0	1	N/A	1	2
30	visualizes	0	0	0	1	N/A	1	2
31	can be traced to	0	0	0	0	N/A	1	1
32	classifies	0	0	0	0	N/A	1	1
33	complies with	0	0	0	0	N/A	1	1
34	defines constraints for	0	0	0	0	N/A	1	1
35	defines context for	0	0	1	0	N/A	0	1
36	defines requirements in	0	0	1	0	N/A	0	1
37	describes abilities of	0	0	0	1	N/A	0	1
38	describes interactions between	0	0	0	1	N/A	0	1

39	describes measured abilities of	0	0	0	0	N/A	1	1
40	describes the need for	0	0	0	1	N/A	0	1
41	expands	0	0	1	0	N/A	0	1
42	exposes	0	0	0	0	N/A	1	1
43	holds	0	0	0	1	N/A	0	1
44	interfaces with	0	0	0	1	N/A	0	1
45	is derived from	0	0	0	0	N/A	1	1
46	is needed to deliver	0	0	0	1	N/A	0	1
47	is realized as	0	0	0	1	N/A	0	1
48	is required at	0	0	0	0	N/A	1	1
49	is traceable to	0	0	0	0	N/A	1	1
50	meets	0	0	0	1	N/A	0	1
51	produces	0	0	0	1	N/A	0	1
52	provides provenance for	0	0	0	0	N/A	1	1
53	realizes	0	0	0	1	N/A	0	1
54	refines	0	0	0	0	N/A	1	1
55	runs	0	0	0	1	N/A	0	1
56	satisfies	0	0	1	0	N/A	0	1
57	shows behavior of	0	0	0	1	N/A	0	1
58	shows the order of execution of	0	0	0	1	N/A	0	1
59	takes places across	0	0	0	0	N/A	1	1
---	TOTAL	5	5	9	48	0	54	121

A.2.2 German research group

A German group of researchers have also attempted to create a requirement ontology for system life cycle processes. In order to present such effort, the rest of this section is divided into concepts and relationships. Concepts define concepts for the ontology in the context of an integrative framework for mechatronic systems (Section A.2.2.1). Based on this foundation, updates and extensions to the core ontology are also presented (Sections A.2.2.2, A.2.2.3 and A.2.2.4). The rest of the section introduces a summary of concepts for the ontology (Section A.2.2.5) based on the research efforts and presents relationships used to define connections between these concepts (Section A.2.2.6).

A.2.2.1 Integrative framework for mechatronic systems

Kernschmidt et al. (2013) presented an integrative framework for mechatronic systems using the concepts of graph theory[52]. Mechatronics is an interdisciplinary field including the following disciplines and systems: mechanical (e.g., mechanical elements, machines, and precision mechanics), electronics (e.g., microelectronics, power electronics, sensor and actuator technology), and information technology (e.g., system theory, control and automation, software engineering, and artificial intelligence) (Isermann, 2005, pp. 1-30; 2009). The elements for the integrative framework for mechatronic systems are presented in Fig. 123. The figure can be interpreted following UML or SysML. The meta-level (i.e., M2) in the figure corresponds to the root concepts in the ontology. The model-level (i.e., M1) is an instance case of the ontology. The intention to create and separate layers is that the higher layer serves as a syntax guidance to create lower layers. Based on the predefined syntax, correctness and completeness can be verified at lower layers of the ontology. Evidently, at this point, the ontology in Fig. 123 is very abstract compared to the one proposed in the COMPASS research project.

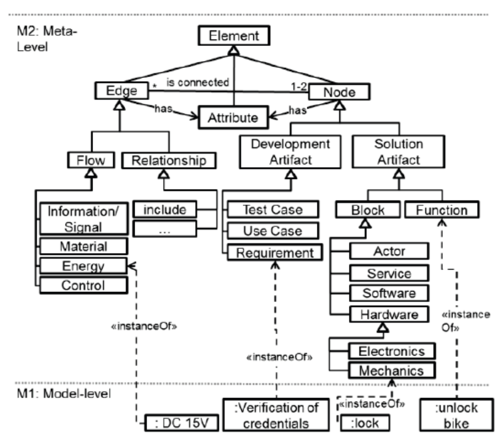
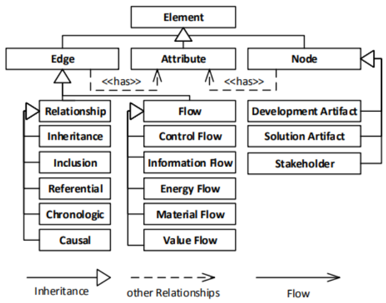


Fig. 123 Specification of the elements for the integration-framework (Kernschmidt et al., 2013)

[52] Graphs are discrete structures consisting of vertices (or nodes) and edges that connect these vertices (Rosen, 2012, p. 641).

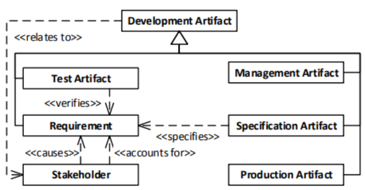
A.2.2.2 *Integrative framework for mechatronic systems' update and expansion: general model, development artifacts, stakeholders, requirements, specification artifacts, management artifacts, solution artifacts, and structure elements*

Future effort from the same group has expanded the ontology in Fig. 123 (Wolfenstetter, Füller, Böhm, Krcmar, & Bründl, 2015). First, Fig. 123 was updated to the generic model in Fig. 124. Generally speaking, both figures have the same fundamental concepts. The generic model in Fig. 124 also makes explicit three types of relationships to relate the types of elements: inheritance, flow, and other relationships. After, some components of the figure have been expanded as shown from Fig. 125 to Fig. 131. Fig. 125 expands the development artifact indicated as a type of node in Fig. 124. Fig. 126 expands the stakeholder type of node in Fig. 124. Fig. 127 expands requirement indicated as a type of development artifact in Fig. 125. Fig. 128 expands the specification artifact indicated as a type of development artifact in Fig. 125. Fig. 129 expands the management artifact indicated as a type of development artifact in Fig. 125. Fig. 130 expands the solution artifact indicated as a type of node in Fig. 124. And finally, Fig. 131 expands the structure element indicated as a type of solution artifact in Fig. 130. Evidently following the relationships defined in the figures (i.e., from Fig. 124 to Fig. 131), all the figures are related to conform a unique ontology to represent what is called the meta-level (i.e., M2) in Fig. 123. Combining from Fig. 124 to Fig. 131, the proposed ontology has 95 concepts. The breaking down of concepts are presented from Fig. 124 to Fig. 131. The sum of concepts on each figure was calculated sequentially from Fig. 124 to Fig. 131. Therefore, following that sequence, if a concept was repeating from a previous figure; it was not added to the sum of concepts. So, just extracting and counting the concepts from the figures may disagree with the defined concepts and the sum of concepts. This update and extension ended with 95 concepts.



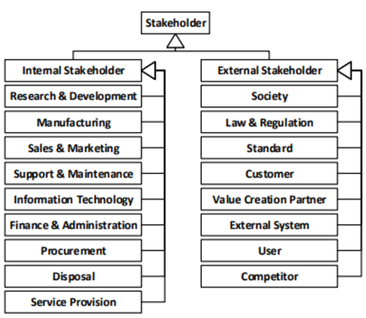
Concepts	Sum of concepts
Element, Edge, Attribute, Node, Relationship, Inheritance, Inclusion, Referential, Chronologic, Causal, Flow, Control flow, Information flow, Energy flow, Material flow, Value flow	19

Fig. 124 General model constructs, constructed from Wolfenstetter et al. (2015)



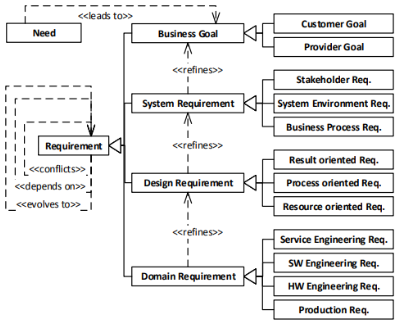
Concepts	Sum of concepts
Test artifact, Requirement, Management artifact, Specification artifact, Production artifact	5

Fig. 125 Development artifacts submodel, constructed from Wolfenstetter et al. (2015)



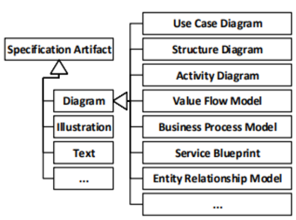
Concepts	Sum of concepts
Internal stakeholder, Research & development, Manufacturing, Sales & marketing, Support & maintenance, Information technology, Finance & administration, Procurement, Disposal, Service provision, External stakeholder, Society, Law & regulations, Standard, Customer, Value creation partner, External system, User, Competitor	19

Fig. 126 Generic stakeholders submodel, constructed from Wolfenstetter et al. (2015)



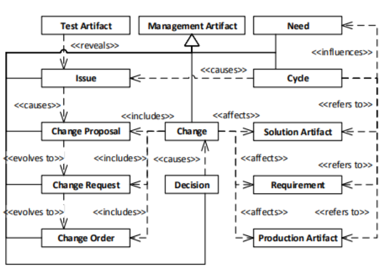
Concepts	Sum of concepts
Need, Business goal, System requirement, Design requirement, Domain requirement, Customer goal, Provider goal, Stakeholder requirement, System environment requirement, Business process requirement, Result oriented requirement, Process oriented requirement, Resource oriented requirement, Service engineering requirement, Software engineering requirement, Hardware engineering requirement, Production requirement	17

Fig. 127 Requirements submodel, constructed from Wolfenstetter et al. (2015)



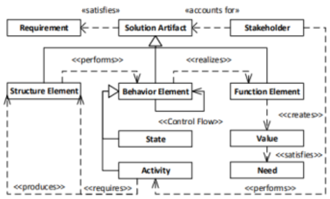
Concepts	Sum of concepts
Diagram, Illustration, Text, Other specification artifact, Use case diagram, Structure diagram, Activity diagram, Value flow model, Business process model, Service blueprint, Entity relationship model, Other diagram	12

Fig. 128 Specification artifacts submodel, constructed from Wolfenstetter et al. (2015)



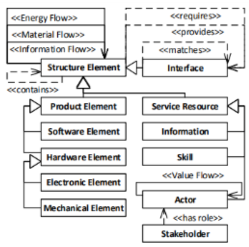
Concepts	Sum of concepts
Issue, Change proposal, Change request, Change order, Change, Decision, Cycle	7

Fig. 129 Management artifact submodel, constructed from Wolfenstetter et al. (2015)



Concepts	Sum of concepts
Structure element, Behavior element, Function element, State, Activity, Value	6

Fig. 130 Solution artifacts submodel, constructed from Wolfenstetter et al. (2015)



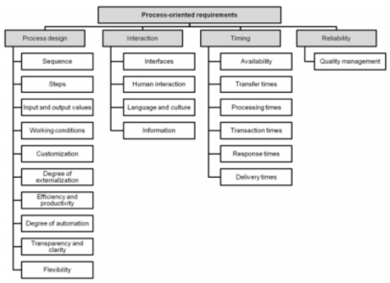
Concepts	Sum of concepts
Interface, Production element, Software element, Hardware element, Electronic element, Mechanical element, Service resource, Information, Skill, Actor	10

Fig. 131 Structure elements submodel, constructed from Wolfenstetter et al. (2015)

A.2.2.3 Integrative framework for mechatronic systems expansion to requirements: process oriented, resources oriented, and product oriented

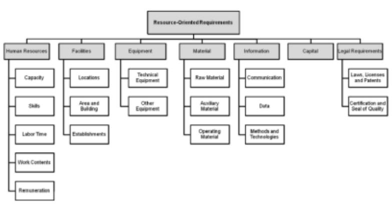
As the subject of requirements is of major importance for this research, the origin of the requirement submodel in Fig. 127 is investigated. Berkovich, Leimeister, Hoffmann, and Krcmar (2014), including authors from the same research group, created the requirement submodel. Interested readers in the methodological aspects to create the requirement submodel can refer to Berkovich et al. (2014). From ontological perspective, Berkovich et al. (2014) extend two types of design requirements (i.e., process oriented requirements, and resource oriented requirements) in Fig. 127. Result oriented requirements, which are also a type of design requirements, are not further extended. The provided reason is that results oriented requirements representing tangible or intangible outcomes depend on the individual customer requirements being expressed in a specific form; thus, it is not possible to provide a taxonomy. Besides the extensions for process oriented requirements, and resource oriented requirements; Berkovich et al. (2014) extend SW and HW engineering requirements in Fig. 127, which are types of domain requirements. Berkovich et al. (2014) combine SW and HW engineering requirements into product requirements. The extensions for process-oriented requirements, resource-oriented requirements, and product requirements are presented from Fig. 132 to Fig. 134 respectively. The extensions from Fig. 132

to Fig. 134 add 65 more concepts to the work from Fig. 124 to Fig. 131. Fig. 132 to Fig. 134 show the 65 concepts and their origin. Therefore, the developed ontology by this group has (95+65) 160 concepts presented from Fig. 124 to Fig. 134.



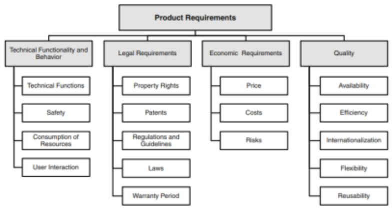
Concepts	Sum of concepts
Process design, Sequence, Steps, Input and output values, Working conditions, Customization, Degree of externalization, Efficiency and productivity, Degree of automation, Transparency and clarity, Interaction, Human interaction, Language and culture, Timing, Transfer times, Processing times, Transaction times, Response times, Delivery times, Reliability, Quality management	21

Fig. 132 Taxonomy of process oriented requirements, constructed from Berkovich et al. (2014)



Concepts	Sum of concepts
Human resources, Capacity, Labor time, Work contents, Remuneration, Facilities, Locations, Area and building, Establishments, Equipment, Technical equipment, Other equipment, Material, Raw material, Auxiliary material, Operating material, Communication, Data, Methods and technologies, Capital, Laws, licenses, and patents, Certification and seal quality	22

Fig. 133 Taxonomy of resource oriented requirements, constructed from Berkovich et al. (2014)



Concepts	Sum of concepts
Product requirements, Technical functionality and behavior, Technical functions, Safety, Consumption of resources, User interaction, Legal requirements, Property rights, Patents, Regulations and guidelines, Laws, Warranty period, Economic requirements, Price, Costs, Risks, Quality, Availability, Efficiency, Internationalization, Flexibility, Reusability	22

Fig. 134 Taxonomy of product requirements, constructed from Berkovich et al. (2014)

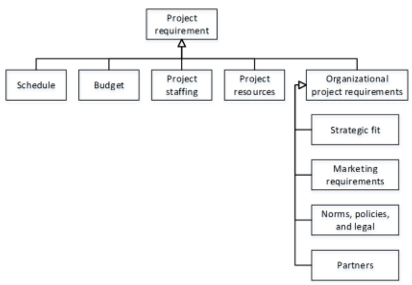
A.2.2.4 Integrative framework for mechatronic systems expansion to requirements: project, functionality, lifecycle, interface, and level of service

Going a last time backwards in time, the same research group has proposed a complementary taxonomy of requirements (Herzfeldt, Briggs, Read, & Krcmar, 2011). The proposed taxonomy of requirements has five categories: 1) project requirement, 2) functionality requirements, 3) lifecycle requirements, 4) interface requirements, and 5) level of service requirements. The categories complement the concepts presented in Fig. 127 and Fig. 134, where the latter was a previous extension of Fig. 127. All the extensions to the requirement submodel in Fig. 127 are summarized in Table 69. The total number of complementing concepts are 41, originated and distributed as shown from Fig. 135 to Fig. 139. Therefore, this research group has created an ontology with (95+65+41) 201 concepts defined from Fig. 124 to Fig. 139.

Table 69 Existing taxonomy and extending models

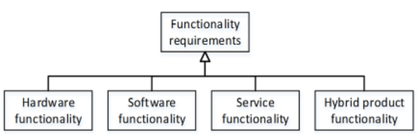
Existing taxonomy/model	Extending model
Requirement submodel (Fig. 127)	Fig. 135 extends a type of requirement.
Requirement submodel (Fig. 127) and taxonomy of product requirements Fig. 134	Fig. 136 extends types of technical functions in Fig. 134, which originally are types of SW and HW engineering requirements in Fig. 127.

	Fig. 136 extends a type of service engineering requirements in Fig. 127.
Requirement submodel (Fig. 127)	Fig. 137 extends a type of business process requirement.
Requirement submodel (Fig. 127)	Fig. 138 extends one more type of domain requirements.
Requirement submodel (Fig. 127)	Fig. 139 extends a type of service engineering requirements.



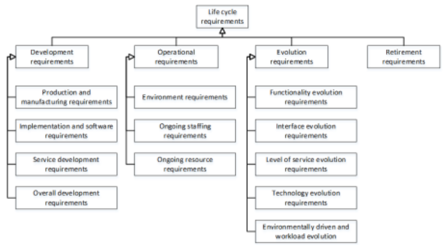
Concepts	Sum of concepts
Project requirement, schedule, budget, project staffing, project resources, organizational project requirements, strategic fit, marketing requirements, norms, policies and legal, partners	10

Fig. 135 Taxonomy of project requirements, constructed from Herzfeldt et al. (2011)



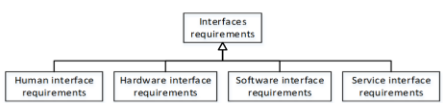
Concepts	Sum of concepts
Functionality requirements, hardware (HW) functionality, software (SW) functionality, service functionality, hybrid functionality	5

Fig. 136 Taxonomy of functionality requirements, constructed from Herzfeldt et al. (2011)



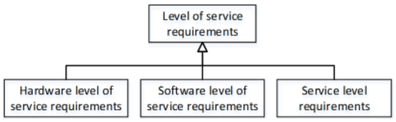
Concepts	Sum of concepts
Life cycle requirements, Development requirements, Production and manufacturing requirements, Implementation and software requirements, Service development requirements, Overall development requirements, Operational requirements, Environment requirements, Ongoing staffing requirements, Ongoing resource requirements, Evolution requirements, Functionality evolution requirements, Interface evolution requirements, Level of service evolution requirements, Technology evolution requirements, Environmentally driven and workload evolution, Retirement requirements	17

Fig. 137 Taxonomy of life cycle requirements, constructed from Herzfeldt et al. (2011)



Concepts	Sum of concepts
Interface requirements, Human interface requirements, Hardware interface requirements, Software interface requirements, Service interface requirements	5

Fig. 138 Taxonomy of interface requirements, constructed from Herzfeldt et al. (2011)



Concepts	Sum of concepts
Level of service requirements, Hardware level of service requirements, Software level of service requirements, Service level requirements	4

Fig. 139 Taxonomy of service requirements, constructed from Herzfeldt et al. (2011)

A.2.2.5 Concepts: summary

This research group presented an ontology called an integrative framework for mechatronic systems. The group has developed the ontology in four efforts. The first effort was the creation of a generic ontology to represent an integrative framework for mechatronic systems. The second efforts adopts the first effort as a foundation to update and extend resulting in 95 concepts defined from Fig. 124 to Fig. 131. Considering that the second effort updates the first one, but keeping almost the same core, concepts from the first effort are not counted. The third effort expands concepts for requirements introducing 65 more concepts defined from Fig. 132 to Fig. 134. The fourth effort expands other types of requirements introducing 41 more concepts from Fig. 135 to Fig. 139. In total, this group has created an ontology with 201 concepts from Fig. 124 to Fig. 139. The 201 unique concepts are summarized in Table 70.

Table 70 German research group and their unique concepts

Group	Concepts
German research group	Activity, Activity diagram, Actor, Area and building, Attribute Auxiliary material, Availability, Behavior element, Budget, Business goal, Business process model, Business process requirement, Capacity, Capital, Causal, Certification and seal quality, Change, Change order, Change proposal, Change request, Chronologic, Communication, Competitor, Consumption of resources, Control flow, Costs, Customer, Customer goal, Customization, Cycle, Data, Decision, Degree of automation, Degree of externalization, Delivery times, Design requirement, Development artifact, Development requirements, Diagram, Disposal, Domain requirement, Economic requirements, Edge, Efficiency, Efficiency and productivity,

	Electronic element, Element, Energy flow, Entity relationship model, Environment requirements, Environmentally driven and workload evolution, Equipment, Establishments, Evolution requirements, External stakeholder, External system, Facilities, Finance & administration, Flexibility, Flow, Function element, Functionality evolution requirements, Functionality requirements, Hardware element, Hardware engineering requirement, Hardware functionality, Hardware interface requirements, Hardware level of service requirements, Human interaction, Human interface requirements, Human resources, Hybrid product functionality, Illustration, Implementation and software requirements, Inclusion, Information, Information flow, Information technology, Inheritance, Input and output values, Interaction, Interface, Interface evolution requirements, Interface requirements, Internal stakeholder, Internationalization, Issue, Labor time, Language and culture, Law & regulations, Laws, Laws, licenses, and patents, Legal requirements, Level of service evolution requirements, Level of service requirements, Life cycle requirements, Locations, Management artifact, Manufacturing, Marketing requirements, Material, Material flow, Mechanical element, Methods and technologies, Need, Node, Norms, policies and legal, Ongoing resource requirements, Ongoing staffing requirements, Operating material, Operational requirements, Organizational project requirements, Other diagram, Other equipment, Other specification artifact, Overall development requirements, Partners, Patents, Price, Process design, Process oriented requirement, Processing times, Procurement, Product requirements, Production and manufacturing requirements, Production artifact, Production element, Production requirement, Project requirements, Project resources, Project staffing, Property rights, Provider goal, Quality, Quality management, Raw material, Referential, Regulations and guidelines, Relationship, Reliability, Remuneration, Requirement, Research & development, Resource oriented requirement, Response times, Result oriented requirement, Retirement requirements, Reusability, Risks, Safety, Sales & marketing, Schedule, Sequence, Service blueprint, Service development requirements,

	Service engineering requirement, Service functionality, Service interface requirements, Service level requirements, Service provision, Service resource, Skill, Society, Software element, Software engineering requirement, Software functionality, Software interface requirements, Software level of service requirements, Solution artifact, Specification artifact, Stakeholder, Stakeholder requirement, Standard, State, Steps, Strategic fit, Structure diagram, Structure element, Support & maintenance, System environment requirement, System requirement, Technical equipment, Technical functionality and behavior, Technical functions, Technology evolution requirements, Test artifact, Text, Timing, Transaction times, Transfer times, Transparency and clarity, Use case diagram, User, User interaction, Value creation partner, Value, Value flow, Value flow model, Warranty period, Work contents, Working conditions

A.2.2.6 Relationships

Besides concepts, ontologies are also composed of relationships to connect these concepts. Fig. 123 to Fig. 139 show different kinds of relationships. The research group also uses SysML to express relationships. SysML relationships, multiplicities, and notations were previously defined in Table 66 and Table 67. Fig. 123 to Fig. 139 have generic relationships in SysML, and specific associations. Generic relationships are standard, but specific associations include the verb phrase variable. Considering this variable, there are several instances of association which can be considered as specific associations. In total, the research group defined 56 instances of associations. From the 56 relationships, 33 instances conform unique instances of association, while the remaining 23 are repeating 12 instances from the 33 unique instances. The unique 33 instances of associations are defined in Table 71. The repeating 12 instances and their relative frequency can be inferred from the same table, which are defined by the values greater than 1 in the column titled sum. Table 71 excludes Fig. 126, Fig. 128, and Fig. 132 to Fig. 139 because they only present generic relationships, i.e., they do not introduce any instance of association.

Table 71 Instances of association and their source by German research group

#	Instance of association	Fig. 123	Fig. 124	Fig. 125	Fig. 127	Fig. 129	Fig. 130	Fig. 131	Sum
1	causes	0	0	1	0	3	0	0	4
2	has	2	2	0	0	0	0	0	4
3	instance of	4	0	0	0	0	0	0	4
4	affects	0	0	0	0	3	0	0	3
5	evolves to	0	0	0	1	2	0	0	3
6	includes	0	0	0	0	3	0	0	3
7	refers to	0	0	0	0	3	0	0	3
8	refines	0	0	0	3	0	0	0	3
9	accounts for	0	0	1	0	0	1	0	2
10	performs	0	0	0	0	0	2	0	2
11	requires	0	0	0	0	0	1	1	2
12	satisfies	0	0	0	0	0	2	0	2
13	conflicts	0	0	0	1	0	0	0	1
14	contains	0	0	0	0	0	0	1	1
15	control flow	0	0	0	0	0	1	0	1
16	creates	0	0	0	0	0	1	0	1
17	depends on	0	0	0	1	0	0	0	1
18	energy flow	0	0	0	0	0	0	1	1
19	has role	0	0	0	0	0	0	1	1
20	influences	0	0	0	0	1	0	0	1
21	information flow	0	0	0	0	0	0	1	1
22	is connected	1	0	0	0	0	0	0	1
23	leads to	0	0	0	1	0	0	0	1
24	matches	0	0	0	0	0	0	1	1
25	material flow	0	0	0	0	0	0	1	1
26	produces	0	0	0	0	0	1	0	1
27	provides	0	0	0	0	0	0	1	1

28	realizes	0	0	0	0	0	1	0	1
29	relates to	0	0	1	0	0	0	0	1
30	reveals	0	0	0	0	1	0	0	1
31	specifies	0	0	1	0	0	0	0	1
32	value flow	0	0	0	0	0	0	1	1
33	verifies	0	0	1	0	0	0	0	1
---	TOTAL	7	2	5	7	16	10	9	56

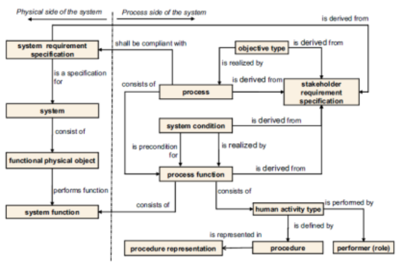
A.2.3 Leo van Ruijven, Croon Elektrotechniek, the Netherlands

van Ruijven (2012, 2013, 2015) has also tried to create a requirements ontology for system engineering. The author effort started in 2012. In this effort, the international standard ISO/IEC/IEEE (2008) was used to define the scope of systems engineering (van Ruijven, 2012). van Ruijven (2012) claims that in practice every company interprets the international standard slightly differently, so it is imperative to define explicitly and unambiguously the system life cycle processes in the standard. van Ruijven (2012) employed ISO/IEC/IEEE (2008) in representing system life cycle processes, but the author indicates that his ontology normalizes the concepts from the standard. Even though the normalization is not explicitly mapped from the standard to the proposed ontology, van Ruijven (2012) ontology is relevant to this research.

The complete ontology has been presented in three different publications. Each of the publication is discussed in detail in Section A.2.3.1, Section A.2.3.2, and Section A.2.3.3. After that, a summary of concepts is presented in Section A.2.3.4. The section concludes presenting the relationships used to connect the concepts in Section A.2.3.5.

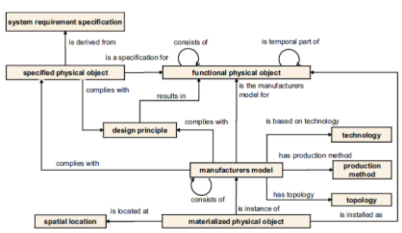
A.2.3.1 Systems engineering ontology: original

The first publication presented 10 information models with 186 concepts that conform the ontology for systems engineering by van Ruijven (2012). The information models are presented from Fig. 140 to Fig. 149. Considering that the information models overlap to integrate the complete ontology, there are 46 repeating concepts. These concepts and the number of times repeating are: activity (2), activity status (1), assumption (1), consequence, (1), document (3), environment (1), functional physical object (4), issue (2), manufacturers model (1), materialized physical object (2), objective (1), party (3), performer role (1), port interaction specification (2), process (2), process function (1), requirement specification (6), risk (1), risk mitigation measure (1), specified physical object (2), system (3), system function (1), system life cycle state (2), system requirement specification (1), and work package deliverable item (1). Out of the 46 repeating concepts, 25 concepts repeat at least one time. Moreover, if the total number of concepts is 186, by removing the 46 repeating concepts, the total of non-repeating concepts in the ontology is 140. The breakdown of non-repeating concepts is defined from Fig. 140 to Fig. 149. Repeating concepts are only allocated to the figure where they appear the first time, where initial time is considered Fig. 140 and progresses until Fig. 149.



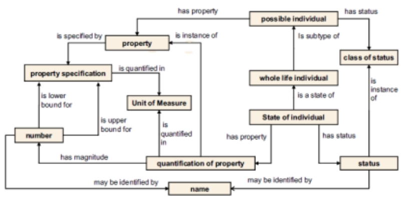
Concepts	Sum of concepts
System requirement specification, System, Functional physical object, System function, Process, System condition, Process function, Procedure representation, Objective type, Stakeholder requirement specification, Human activity type, Procedure, Performer (role)	13

Fig. 140 Information model of representing the process side and physical side of a system, constructed from van Ruijven (2012)



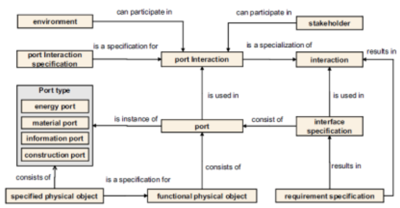
Concepts	Sum of concepts
Specified physical object, Design principle, Manufacturers model, Technology, Production method, Topology, Materialized physical object, Spatial location	8

Fig. 141 Fundamental physical system elements, constructed from van Ruijven (2012)



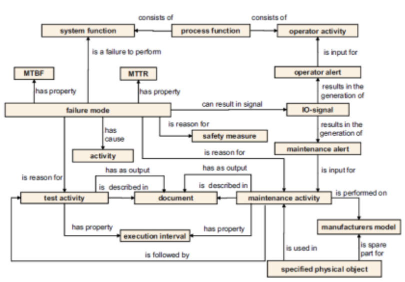
Concepts	Sum of concepts
Property specification, Number, Property, Unit of measure, Quantification of property, Name Possible individual, Whole life individual, State of individual, Class of status, Status	11

Fig. 142 The property and status model of possible individuals, constructed from van Ruijven (2012)



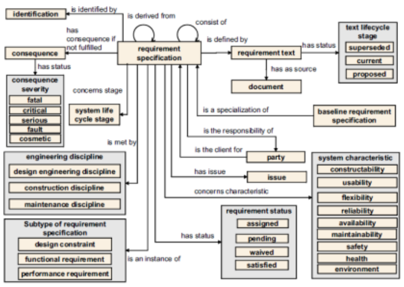
Concepts	Sum of concepts
Environment, Port interaction specification, Port type, Energy port, Material port, Information port, Construction port, Port interaction, Port, Stakeholder, Interaction, Interface specification, Requirement specification	13

Fig. 143 Port principle to model all relevant interactions within and between systems and the outside world of the system, constructed from van Ruijven (2012)



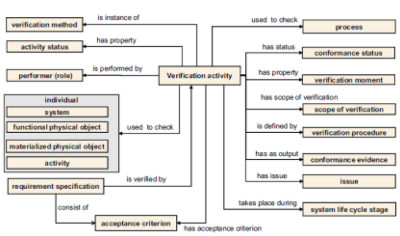
Concepts	Sum of concepts
MTBF, Failure mode, Activity, Test activity, MTTR, Document, Execution interval, Safety measure, Operator activity, Operator alert, IO-signal, Maintenance alert, Maintenance activity	13

Fig. 144 Information model of the failure mode and effect analysis process, constructed from van Ruijven (2012)



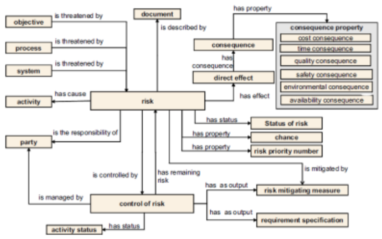
Concepts	Sum of concepts
Identification, Consequence, Consequence severity, Fatal, Critical, Serious, Fault, Cosmetic, Engineering discipline, Design engineering discipline, Construction discipline, Maintenance discipline, Subtype of requirement specification, Design constraint, Functional requirement, Performance requirement, System life cycle stage, Requirement text, Party, Issue, Requirement status, Assigned, Pending, Waived, Satisfied, Text lifecycle stage, Superseded, Current, Proposed, Baseline requirement specification, System characteristics, Constructability, Usability, Flexibility, Reliability, Availability, Maintainability, Safety, Health	39

Fig. 145 Information model of a requirement specification, constructed from van Ruijven (2012)



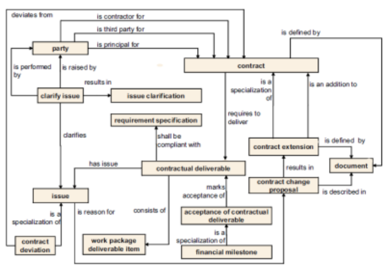
Concepts	Sum of concepts
Verification method, Activity status, Individual, Acceptance criterion, Verification activity, Conformance status, Verification moment, Scope of verification, Verification procedure, Conformance evidence	10

Fig. 146 Information model of a verification activity, constructed from van Ruijven (2012)



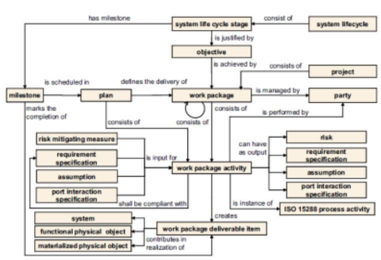
Concepts	Sum of concepts
Objective, Control of risk, Risk, Direct effect, Consequence property, Cost consequence, Time consequence, Quality consequence, Safety consequence, Environmental consequence, Availability consequence, Status of risk, Chance, Risk priority number, Risk mitigation measure	15

Fig. 147 Information model for a risk and risk control activities, constructed from van Ruijven (2012)



Concepts	Sum of concepts
Clarify issue, Contract deviation, Issue clarification, Contractual deliverable, Work package deliverable item, Acceptance of contractual deliverable, Financial milestone, Contract, Contract extension, Contract change proposal	10

Fig. 148 Information model for contracts and contract changes, constructed from van Ruijven (2012)

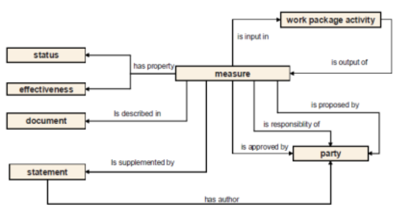


Concepts	Sum of concepts
Milestone, Plan, Assumption, Work package, Work package activity, System lifecycle, Project, ISO 15288 process activity	8

Fig. 149 Information model for the items relevant to the context of a work breakdown structure, constructed from van Ruijven (2012)

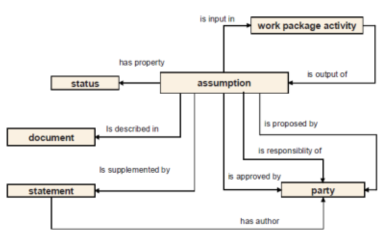
A.2.3.2 Systems engineering ontology: extension 1

In an ongoing effort, van Ruijven (2013) introduced 12 information models in a second publication. This publication includes the 10 information models defined from Fig. 140 to Fig. 149, plus the two additional ones in Fig. 150 and Fig. 151. The two additional models include 13 concepts. From the 13 concepts, 3 concepts are new to the concepts presented from Fig. 140 to Fig. 149. The rest of 10 concepts repeats. The repeating concepts and their frequency are: document (2), party (2), status (2), work package activity (2), assumption (1), and statement (1). The new concepts are defined in Fig. 150 and Fig. 151. Besides the new concepts, there are two conceptualization changes in the core 10 information models. First, van Ruijven (2013) replaced the concept *objective type* in Fig. 140 to *objective*. Second, the author added *document is input for work package activity* to Fig. 149. The conceptualization changes are not discussed by the author; however, they may be significant from ontology point of view. Since the rationale of the changes is unknown, the original concepts will be considered in further discussion of this research.



Concepts	Sum of concepts
Effectiveness, Statement, Measure	3

Fig. 150 A basic information model for a measure, constructed from van Ruijven (2013)

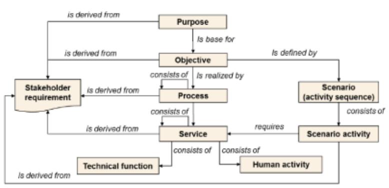


Concepts	Sum of concepts
N/A	0

Fig. 151 A basic information model of an assumption, constructed from van Ruijven (2013)

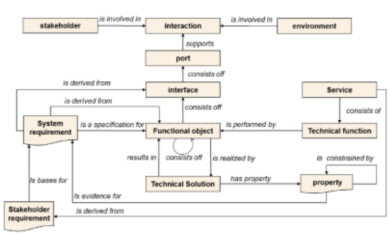
A.2.3.3 Systems engineering ontology: extension 2

On a third publication, van Ruijven (2015) proposed 5 additional information models. The models are presented from Fig. 152 to Fig. 156. From the models, Fig. 152 to Fig. 155 are considered new models while Fig. 156 is considered an extension to the model in Fig. 146. Although Fig. 156 is an extension, it was included as it also differentiates validation from verification in the model. The 5 additional models represent 123 concepts: 43 new concepts, and 80 repeating concepts. Repeating concepts are accounted based on all the information models from Fig. 140 to Fig. 156. The new concepts are defined from Fig. 152 to Fig. 156. The repeating concepts are 63 with repetition frequency distributed as follows: activity (3), party (3), process (3), life cycle stage (2), role (2), service (2), stakeholder requirement (2), technical function (2), environment (2), identification (2), issue (2), objective (2), requirement text (2), risk (2), activity status (1), assigned (1), assumption (1), availability (1), conformance status (1), consequence severity (1), constructability (1), cosmetic (1), critical (1), current (1), description (1), design constraint (1), document (1), fatal (1), fault (1), flexibility (1), function (1), functional requirement (1), health (1), human activity (1), information object (1), interaction (1), maintainability (1), pending (1), performance requirement (1), performer (role) (1), port (1), procedure (1), property (1), proposed (1), reliability (1), requirement (1), requirement status (1), safety (1), satisfied (1), serious (1), spatial location (1), stakeholder (1), superseded (1), system (1), system requirement (1), text life cycle stage (1), thing 5 (1), usability (1), V&V activity (1), V&V method (1), version identification (1), waived (1), and work package (1).



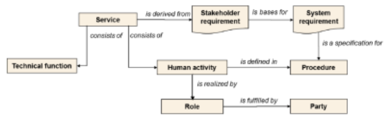
Concepts	Sum of concepts
Stakeholder requirement, Purpose, Service, Technical function, Human activity, Scenario activity, Scenario (activity sequence)	7

Fig. 152 Information model representing the stakeholder requirement definition process, constructed from van Ruijven (2015)



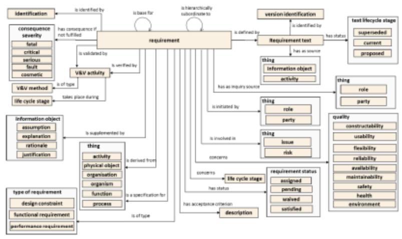
Concepts	Sum of concepts
Interface, Functional object, System requirement, Technical solution	4

Fig. 153 Information model representing the requirement analysis process, constructed from van Ruijven (2015)



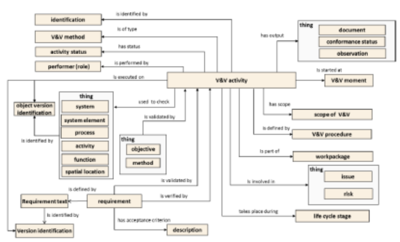
Concepts	Sum of concepts
Role	1

Fig. 154 Information model representing the operational and maintenance process, constructed from van Ruijven (2015)



Concepts	Sum of concepts
V&V method, Life cycle stage, V&V activity, Information object, Explanation, Rationale, Justification, Type of requirement, Thing 1, Physical object, Organization, Organism, Function, Requirement, Version identification, Thing 2, Thing 3, Thing 4, Thing 5, Description, Quality	21

Fig. 155 Detailed information model for a requirement, constructed from van Ruijven (2015)



Concepts	Sum of concepts
Object version identification, Thing 6, System element, Thing 7, Method, Thing 8, Observation, V&V moment, Scope of V&V, V&V procedure	10

Fig. 156 Information model of a typical verification & validation (V&V) activity, constructed from van Ruijven (2015)

A.2.3.4 Concepts: summary

In conclusion, van Ruijven (2012, 2013, 2015) has created a complete ontology with 186 concepts. The diagrams from Fig. 140 to Fig. 156 illustrate 322 concepts. From those concepts, 186 concepts are unique, and 136 concepts are repeating. The repeating 136 concepts are connecting concepts needed to integrate the information models into one ontology. The 186 unique concepts are summarized in Table 72.

Table 72 Leo van Ruijven and their unique concepts

Group	Concepts
Leo van Ruijven	Acceptance criterion, Acceptance of contractual deliverable, Activity, Activity status, Assigned, Assumption, Availability, Availability consequence, Baseline requirement specification, Chance, Clarify issue, Class of status, Conformance evidence, Conformance status, Consequence, Consequence property, Consequence severity, Constructability, Construction discipline, Construction port, Contract, Contract change proposal, Contract deviation, Contract extension, Contractual deliverable, Control of risk, Cosmetic, Cost consequence, Critical, Current, Description, Design constraint, Design engineering discipline, Design principle, Direct effect, Document, Effectiveness, Energy port, Engineering discipline, Environment, Environmental consequence, Execution interval, Explanation, Failure mode, Fatal, Fault, Financial milestone, Flexibility, Function, Functional object, Functional physical object, Functional requirement, Health, Human activity, Human activity type, Identification, Individual, Information object, Information port, Interaction, Interface, Interface specification, IO-signal, ISO 15288 process activity, Issue, Issue clarification, Justification, Life cycle stage, Maintainability, Maintenance activity, Maintenance alert, Maintenance discipline, Manufacturers model, Material port, Materialized physical object, Measure, Method, Milestone, MTBF, MTTR, Name, Number, Object version identification, Objective, Objective type, Observation, Operator activity, Operator alert, Organism, Organization, Party, Pending, Performance requirement, Performer (role), Physical object, Plan, Port, Port interaction, Port interaction specification, Port type, Possible individual, Procedure, Procedure representation, Process, Process function, Production method, Project, Property, Property specification, Proposed, Purpose, Quality, Quality consequence, Quantification of property, Rationale, Reliability, Requirement, Requirement specification, Requirement status, Requirement text, Risk, Risk mitigation measure, Risk priority number, Role, Safety, Safety consequence, Safety measure, Satisfied, Scenario (activity sequence), Scenario activity,

	Scope of V&V, Scope of verification, Serious, Service, Spatial location, Specified physical object, Stakeholder, Stakeholder requirement, Stakeholder requirement specification, State of individual, Statement, Status, Status of risk, Subtype of requirement specification, Superseded, System, System characteristics, System condition, System element, System function, System life cycle stage, System lifecycle, System requirement, System requirement specification, Technical function, Technical solution, Technology, Test activity, Text lifecycle stage, Thing 1, Thing 2, Thing 3, Thing 4, Thing 5, Thing 6, Thing 7, Thing 8, Time consequence, Topology, Type of requirement, Unit of measure, Usability, V&V activity, V&V method, V&V moment, V&V procedure, Verification activity, Verification method, Verification moment, Verification procedure, Version identification, Waived, Whole life individual, Work package, Work package activity, Work package deliverable item

A.2.3.5 Relationships

Besides concepts, ontologies are also composed of relationships to connect these concepts. Fig. 140 to Fig. 156 show different kind of relationships. van Ruijven (2012, 2013, 2015) employs RDF (Resource Description Framework) syntax to describe the information models in his ontology. Therefore, the information models conform to the generic structure of an RDF graph (see Fig. 157), previously discussed in the literature review section. Subjects and objects in an RDF graph are the concepts define from Fig. 140 to Fig. 156. The predicate in an RDF graph is a verb phrase variable. The verb phrase variable can take the form of any verb phrase, which can represent both generic relationships and specific associations in SysML. Considering this variable, Fig. 140 to Fig. 156 use several instances of predicates. In total, van Ruijven (2012, 2013, 2015) utilized 280 instances of predicates. From the 280 instances of predicates, 111 instances conform unique instances of predicates, while the remaining 169 are repeating 46 instances from the 111 unique instances. The unique 111 instances of predicates are defined in both Table 73 and Table 74. The repeating 46 instances of predicates and their relative frequency can be inferred from Table 74, which are defined by the values greater than 1 in the column titled sum. The sum column in the table represents the sum of each instance of predicated compiled from the defined appearances in both Table 73 and Table 74. In general, both Table 73 and Table 74 shall be one table; however, they were split to define the source of the data which in turn improve readability and enable reproducibility of the data and tables.

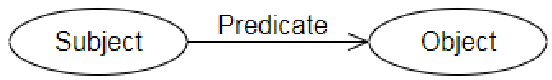


Fig. 157 RDF graph (W3C, 2014)

Table 73 Instances of predicates and their source by Leo van Ruijven

#	Instances of predicates	Fig. 140	Fig. 141	Fig. 142	Fig. 143	Fig. 144	Fig. 145	Fig. 146	Fig. 147	Fig. 148
1	consists of	4	2	0	3	2	1	1	0	1
2	is derived from	5	1	0	0	0	1	0	0	0
3	has property	0	0	2	0	4	0	2	3	0
4	has status	0	0	2	0	0	3	1	2	0
5	is defined by	1	0	0	0	0	1	1	0	2
6	is a specification for	1	1	0	2	0	0	0	0	0
7	results in	0	1	0	2	0	0	0	0	2
8	is instance of	0	1	2	1	0	0	1	0	0
9	is performed by	1	0	0	0	0	0	1	0	1
10	is identified by	0	0	0	0	0	1	0	0	0
11	is a specialization of	0	0	0	1	0	1	0	0	3
12	has as output	0	0	0	0	2	0	1	2	0
13	is described in	0	0	0	0	2	0	0	0	1
14	is realized by	2	0	0	0	0	0	0	0	0
15	is reason for	0	0	0	0	3	0	0	0	1
16	is involved in	0	0	0	0	0	0	0	0	0
17	is base for	0	0	0	0	0	0	0	0	0
18	is used in	0	0	0	2	1	0	0	0	0
19	is threatened by	0	0	0	0	0	0	0	3	0
20	has issue	0	0	0	0	0	1	1	0	1
21	complies with	0	3	0	0	0	0	0	0	0

22	used to check	0	0	0	0	0	0	2	0	0
23	shall be compliant with	1	0	0	0	0	0	0	0	1
24	is input for	0	0	0	0	2	0	0	0	0
25	takes place during	0	0	0	0	0	0	1	0	0
26	is verified by	0	0	0	0	0	0	1	0	0
27	has acceptance criterion	0	0	0	0	0	0	1	0	0
28	is validated by	0	0	0	0	0	0	0	0	0
29	is supplemented by	0	0	0	0	0	0	0	0	0
30	is of type	0	0	0	0	0	0	0	0	0
31	results in the generation of	0	0	0	0	2	0	0	0	0
32	may be identified by	0	0	2	0	0	0	0	0	0
33	is the responsibility of	0	0	0	0	0	1	0	1	0
34	is quantified in	0	0	2	0	0	0	0	0	0
35	has cause	0	0	0	0	1	0	0	1	0
36	can participate in	0	0	0	2	0	0	0	0	0
37	is managed by	0	0	0	0	0	0	0	1	0
38	has consequence if not fulfilled	0	0	0	0	0	1	0	0	0
39	has as source	0	0	0	0	0	1	0	0	0
40	is responsible of	0	0	0	0	0	0	0	0	0
41	is proposed by	0	0	0	0	0	0	0	0	0
42	is output of	0	0	0	0	0	0	0	0	0
43	is input in	0	0	0	0	0	0	0	0	0
44	is approved by	0	0	0	0	0	0	0	0	0
45	has author	0	0	0	0	0	0	0	0	0
46	concerns	0	0	0	0	0	0	0	0	0
47	requires to deliver	0	0	0	0	0	0	0	0	1
48	performs function	1	0	0	0	0	0	0	0	0

49	marks acceptance of	0	0	0	0	0	0	0	0	1
50	is upper bound for	0	0	1	0	0	0	0	0	0
51	is third party for	0	0	0	0	0	0	0	0	1
52	is the manufacturers mode for	0	1	0	0	0	0	0	0	0
53	is the client for	0	0	0	0	0	1	0	0	0
54	is temporal part of	0	1	0	0	0	0	0	0	0
55	is subtype of	0	0	1	0	0	0	0	0	0
56	is specified by	0	0	1	0	0	0	0	0	0
57	is spare part for	0	0	0	0	1	0	0	0	0
58	is represented in	1	0	0	0	0	0	0	0	0
59	is raised by	0	0	0	0	0	0	0	0	1
60	is principal for	0	0	0	0	0	0	0	0	1
61	is precondition for	1	0	0	0	0	0	0	0	0
62	is performed on	0	0	0	0	1	0	0	0	0
63	is mitigated by	0	0	0	0	0	0	0	1	0
64	is met by	0	0	0	0	0	1	0	0	0
65	is lower bound for	0	0	1	0	0	0	0	0	0
66	is located at	0	1	0	0	0	0	0	0	0
67	is installed as	0	1	0	0	0	0	0	0	0
68	is followed by	0	0	0	0	1	0	0	0	0
69	is described by	0	0	0	0	0	0	0	1	0
70	is controlled by	0	0	0	0	0	0	0	1	0
71	is contractor for	0	0	0	0	0	0	0	0	1
72	is based on technology	0	1	0	0	0	0	0	0	0
73	is an instance of	0	0	0	0	0	1	0	0	0
74	is an addition to	0	0	0	0	0	0	0	0	1
75	is a state of	0	0	1	0	0	0	0	0	0
76	is a failure to perform	0	0	0	0	1	0	0	0	0
77	has topology	0	1	0	0	0	0	0	0	0

78	has scope of verification	0	0	0	0	0	0	1	0	0
79	has remaining risk	0	0	0	0	0	0	0	1	0
80	has production method	0	1	0	0	0	0	0	0	0
81	has magnitude	0	0	1	0	0	0	0	0	0
82	has effect	0	0	0	0	0	0	0	1	0
83	has consequence	0	0	0	0	0	0	0	1	0
84	deviates from	0	0	0	0	0	0	0	0	1
85	concerns stage	0	0	0	0	0	1	0	0	0
86	concerns characteristic	0	0	0	0	0	1	0	0	0
87	clarifies	0	0	0	0	0	0	0	0	1
88	can result in signal	0	0	0	0	1	0	0	0	0
89	supports	0	0	0	0	0	0	0	0	0
90	requires	0	0	0	0	0	0	0	0	0
91	marks the completion of	0	0	0	0	0	0	0	0	0
92	is started at	0	0	0	0	0	0	0	0	0
93	is scheduled in	0	0	0	0	0	0	0	0	0
94	is part of	0	0	0	0	0	0	0	0	0
95	is justified by	0	0	0	0	0	0	0	0	0
96	is initiated by	0	0	0	0	0	0	0	0	0
97	is hierarchically subordinate to	0	0	0	0	0	0	0	0	0
98	is fulfilled by	0	0	0	0	0	0	0	0	0
99	is executed on	0	0	0	0	0	0	0	0	0
100	is evidence for	0	0	0	0	0	0	0	0	0
101	is defined in	0	0	0	0	0	0	0	0	0
102	is constrained by	0	0	0	0	0	0	0	0	0
103	is achieved by	0	0	0	0	0	0	0	0	0
104	has scope	0	0	0	0	0	0	0	0	0

105	has output	0	0	0	0	0	0	0	0	0
106	has milestone	0	0	0	0	0	0	0	0	0
107	has as inquiry source	0	0	0	0	0	0	0	0	0
108	defines the delivery of	0	0	0	0	0	0	0	0	0
109	creates	0	0	0	0	0	0	0	0	0
110	contributes in realization of	0	0	0	0	0	0	0	0	0
111	can have as output	0	0	0	0	0	0	0	0	0
---	TOTAL	18	16	16	13	24	17	15	19	22

Table 74 Instances of predicates and their source by Leo van Ruijven

#	Instances of predicates	Fig. 149	Fig. 150	Fig. 151	Fig. 152	Fig. 153	Fig. 154	Fig. 155	Fig. 156	Sum
1	consists of	5	0	0	5	4	2	0	0	30
2	is derived from	0	0	0	5	3	1	1	0	17
3	has property	0	1	1	0	1	0	0	0	14
4	has status	0	0	0	0	0	0	2	1	11
5	is defined by	0	0	0	1	0	0	1	2	9
6	is a specification for	0	0	0	0	1	1	1	0	7
7	results in	0	0	0	0	1	0	0	0	6
8	is instance of	1	0	0	0	0	0	0	0	6
9	is performed by	1	0	0	0	1	0	0	1	6
10	is identified by	0	0	0	0	0	0	2	3	6
11	is a specialization of	0	0	0	0	0	0	0	0	5
12	has as output	0	0	0	0	0	0	0	0	5
13	is described in	0	1	1	0	0	0	0	0	5
14	is realized by	0	0	0	1	1	1	0	0	5
15	is reason for	0	0	0	0	0	0	0	0	4
16	is involved in	0	0	0	0	2	0	1	1	4
17	is base for	0	0	0	1	1	1	1	0	4

18	is used in	0	0	0	0	0	0	0	0	3
19	is threatened by	0	0	0	0	0	0	0	0	3
20	has issue	0	0	0	0	0	0	0	0	3
21	complies with	0	0	0	0	0	0	0	0	3
22	used to check	0	0	0	0	0	0	0	1	3
23	shall be compliant with	1	0	0	0	0	0	0	0	3
24	is input for	1	0	0	0	0	0	0	0	3
25	takes place during	0	0	0	0	0	0	1	1	3
26	is verified by	0	0	0	0	0	0	1	1	3
27	has acceptance criterion	0	0	0	0	0	0	1	1	3
28	is validated by	0	0	0	0	0	0	1	2	3
29	is supplemented by	0	1	1	0	0	0	1	0	3
30	is of type	0	0	0	0	0	0	2	1	3
31	results in the generation of	0	0	0	0	0	0	0	0	2
32	may be identified by	0	0	0	0	0	0	0	0	2
33	is the responsibility of	0	0	0	0	0	0	0	0	2
34	is quantified in	0	0	0	0	0	0	0	0	2
35	has cause	0	0	0	0	0	0	0	0	2
36	can participate in	0	0	0	0	0	0	0	0	2
37	is managed by	1	0	0	0	0	0	0	0	2
38	has consequence if not fulfilled	0	0	0	0	0	0	1	0	2
39	has as source	0	0	0	0	0	0	1	0	2
40	is responsible of	0	1	1	0	0	0	0	0	2
41	is proposed by	0	1	1	0	0	0	0	0	2
42	is output of	0	1	1	0	0	0	0	0	2
43	is input in	0	1	1	0	0	0	0	0	2
44	is approved by	0	1	1	0	0	0	0	0	2

45	has author	0	1	1	0	0	0	0	0	2
46	concerns	0	0	0	0	0	0	2	0	2
47	requires to deliver	0	0	0	0	0	0	0	0	1
48	performs function	0	0	0	0	0	0	0	0	1
49	marks acceptance of	0	0	0	0	0	0	0	0	1
50	is upper bound for	0	0	0	0	0	0	0	0	1
51	is third party for	0	0	0	0	0	0	0	0	1
52	is the manufacturers mode for	0	0	0	0	0	0	0	0	1
53	is the client for	0	0	0	0	0	0	0	0	1
54	is temporal part of	0	0	0	0	0	0	0	0	1
55	is subtype of	0	0	0	0	0	0	0	0	1
56	is specified by	0	0	0	0	0	0	0	0	1
57	is spare part for	0	0	0	0	0	0	0	0	1
58	is represented in	0	0	0	0	0	0	0	0	1
59	is raised by	0	0	0	0	0	0	0	0	1
60	is principal for	0	0	0	0	0	0	0	0	1
61	is precondition for	0	0	0	0	0	0	0	0	1
62	is performed on	0	0	0	0	0	0	0	0	1
63	is mitigated by	0	0	0	0	0	0	0	0	1
64	is met by	0	0	0	0	0	0	0	0	1
65	is lower bound for	0	0	0	0	0	0	0	0	1
66	is located at	0	0	0	0	0	0	0	0	1
67	is installed as	0	0	0	0	0	0	0	0	1
68	is followed by	0	0	0	0	0	0	0	0	1
69	is described by	0	0	0	0	0	0	0	0	1
70	is controlled by	0	0	0	0	0	0	0	0	1
71	is contractor for	0	0	0	0	0	0	0	0	1
72	is based on technology	0	0	0	0	0	0	0	0	1
73	is an instance of	0	0	0	0	0	0	0	0	1

74	is an addition to	0	0	0	0	0	0	0	0	1
75	is a state of	0	0	0	0	0	0	0	0	1
76	is a failure to perform	0	0	0	0	0	0	0	0	1
77	has topology	0	0	0	0	0	0	0	0	1
78	has scope of verification	0	0	0	0	0	0	0	0	1
79	has remaining risk	0	0	0	0	0	0	0	0	1
80	has production method	0	0	0	0	0	0	0	0	1
81	has magnitude	0	0	0	0	0	0	0	0	1
82	has effect	0	0	0	0	0	0	0	0	1
83	has consequence	0	0	0	0	0	0	0	0	1
84	deviates from	0	0	0	0	0	0	0	0	1
85	concerns stage	0	0	0	0	0	0	0	0	1
86	concerns characteristic	0	0	0	0	0	0	0	0	1
87	clarifies	0	0	0	0	0	0	0	0	1
88	can result in signal	0	0	0	0	0	0	0	0	1
89	supports	0	0	0	0	1	0	0	0	1
90	requires	0	0	0	1	0	0	0	0	1
91	marks the completion of	1	0	0	0	0	0	0	0	1
92	is started at	0	0	0	0	0	0	0	1	1
93	is scheduled in	1	0	0	0	0	0	0	0	1
94	is part of	0	0	0	0	0	0	0	1	1
95	is justified by	1	0	0	0	0	0	0	0	1
96	is initiated by	0	0	0	0	0	0	1	0	1
97	is hierarchically subordinate to	0	0	0	0	0	0	1	0	1
98	is fulfilled by	0	0	0	0	0	1	0	0	1
99	is executed on	0	0	0	0	0	0	0	1	1
100	is evidence for	0	0	0	0	1	0	0	0	1

101	is defined in	0	0	0	0	0	1	0	0	1
102	is constrained by	0	0	0	0	1	0	0	0	1
103	is achieved by	1	0	0	0	0	0	0	0	1
104	has scope	0	0	0	0	0	0	0	1	1
105	has output	0	0	0	0	0	0	0	1	1
106	has milestone	1	0	0	0	0	0	0	0	1
107	has as inquiry source	0	0	0	0	0	0	1	0	1
108	defines the delivery of	1	0	0	0	0	0	0	0	1
109	creates	1	0	0	0	0	0	0	0	1
110	contributes in realization of	1	0	0	0	0	0	0	0	1
111	can have as output	1	0	0	0	0	0	0	0	1
---	TOTAL	19	9	9	14	18	8	23	20	280

A.3 Comparison of the taxonomies

The ontologies presented from Section A.2.1 to Section A.2.3 vary in various aspects. Aspects to differentiate ontologies are syntax & formality, semantics (i.e., number of concepts, and types and number of relationships). In fact, these aspects conform the characteristics of a good ontology defined the literature review chapter. The investigated ontologies are relatively compared in term of syntax & formality in Section A.3.1 and semantics, i.e., number of concepts (Section A.3.2), and types and number of relationships (Section A.3.3). This comparison enables to meet the first non-functional requirement defined in Chapter 4. In addition, this comparison enables to consolidate and integrate the investigated research efforts from concepts point of view in Section A.4.

A.3.1 Syntax & formality

In the literature review section, syntax & formality were defined in terms of the language used to represent an ontology. The ontologies presented from Section A.2.1 to Section A.2.3 have been expressed graphically combining data models (UML and SysML), and ad-hoc hierarchies. Table 75 defines the employed formality and its respective level by group. The level of formality is relative (not absolute) to the compared groups, assigned based on Fig. 158. From the presented ontologies, the COMPASS research group has the highest level of formality.

Table 75 Group, syntax & formality, and level of formality

Group	Syntax & formality	Level of formality
COMPASS research group	UML and SysML	High
German research group	UML and ad-hoc hierarchies	Medium
Leo van Ruijven	Ad-hoc hierarchies	Medium

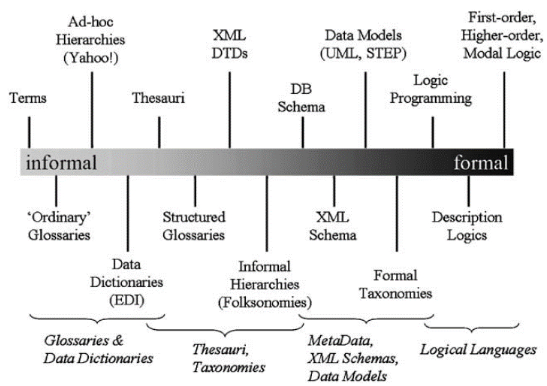


Fig. 158 Degrees of formality to express ontologies (Guarino et al., 2009)

A.3.2 Number of concepts

Even though the ontologies presented from Section A.2.1 to Section A.2.3 try to conceptualize the same scope, their conceptualizations present different concepts and number of concepts. Based on number of concepts in the ontologies, in accordance to Table 76, the German research group proposed more concepts, followed by van Ruijven, and least the COMPASS research group.

Table 76 Group, unique concepts, and total number of unique concepts

Group	Concepts source	Total number of unique concepts
COMPASS research group	Refer to Table 65	114
German research group	Refer to Table 70	201
Leo van Ruijven	Refer to Table 72	186
Total number of concepts		501

A.3.3 Relationships

Even though the ontologies presented from Section A.2.1 to Section A.2.3 try to conceptualize the same scope, their conceptualizations employed diverse types and number of relationships in the representations of the ontologies. Diverse types of relationships refer to multiplicity, generalization/specialization, aggregation, association, and dependency. The number of relationships is associated to the type of relationship “association”.

Considering diversity in relationships, Table 77 defines whether a corresponding research group employs or does not employ a type of relationship. All the presented types of relationships in the table come from UML/SysML notations; hence, they are directly or indirectly related to the abstract’s relationships defined in the corresponding language meta-models specially for class diagrams in UML (Holt, 2007, pp. 56, 83-84) and block definition diagram in SysML (Holt et al., 2011, p. 301). Considering that the ontologies presented by the COMPASS research group and the German research group (partially) were expressed in UML/SysML notations, they support all the types of relationships in the table. On the contrary, van Ruijven employed the RDF syntax notation to express his ontology. In this case, van Ruijven only employs the association type of relationship. Thus, the ontologies by the COMPASS research group and the German research group are more expressive in terms of types of relationships than van Ruijven. However, except for multiplicities, it shall be further investigated whether the verb phrases used by van Ruijven define textually generalizations/specializations, aggregation, or dependencies in order to equalize his ontology expressiveness to the other research groups.

Table 77 Types of relationships and research groups (employs/no employs)

Relationships	COMPASS research group	German research group	Leo van Ruijven
Multiplicity	Yes	Yes	No
Generalization/ specialization	Yes	Yes	No
Aggregation	Yes	Yes	No
Association	Yes	Yes	Yes
Dependency	Yes	Yes	No

Number of relationships are based on the verb phrases employed to define association relationships. The extracted verb phrases to represent association relationships from each group were defined in Table 68, Table 71, and Table 73 & Table 74. Table 78 defines the total number of verb phrases employed by each group. According to this number, van Ruijven employs more verb phrases followed by the COMPASS research group and least the German research group. At this point, the higher the number of verb phrases is interpreted as the more expressive (i.e., specific) in the type of action defined in the verb phrases. However, future development can be conducted to analyze whether if 1) all the employs verb phrases are needed or 2) there are verb phrases synonyms.

Table 78 Group, verb phrases for association relationships, and total number of verb phrases

Group	Verb phrases source	Total number of verb phrases
COMPASS research group	Refer to Table 68	59
German research group	Refer to Table 71	33
Leo van Ruijven	Refer to Table 73 & Table 74	111
Total number of verb phrase		203

To sum up, the ontology by the COMPASS research group and the German research group employ the same highest diversity of types of relationships. But, the ontology by van Ruijven employs the highest number of verb phrases.

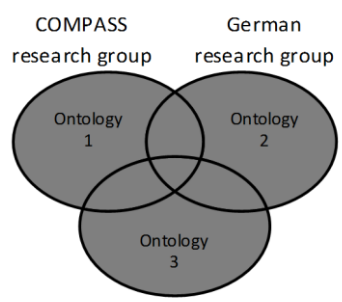
A.4 Consolidating and integrating the taxonomies

Consolidation and integration of taxonomies is dived into two parts. Part 1 in Section A.4.1 deals with concepts. Part 2 in Section A.4.2 deals with relationships. Concepts and relationships are consolidated and integrated using general operations (i.e., union and intersection) in set theory.

A.4.1 Concepts

In total, the three taxonomies (hereafter also discussed as ontologies for simplification purposes), from Section A.2.1 to Section A.2.3, present 501 concepts. From these concepts, 474 concepts are unique among the three ontologies. The 474 unique concepts is the shaded area in the Venn diagram in Fig. 159. The shaded area represents a generalized union, as called by Rosen (2012, pp. 127-134) in set theory, among the concepts in the ontologies created by the research groups.

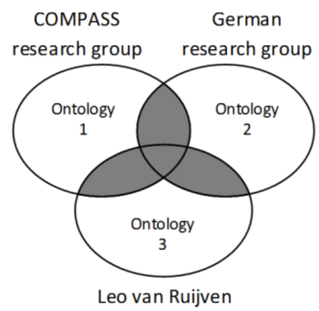
Evidently, each ontology has their identified concepts and relationships which conform the elements of the sets. But for now, the focus is only on concepts[53]. From the 474 unique concepts, 23 concepts repeat one or more times totaling 50 appearances. The 23 repeating concepts and their repeating frequencies are: stakeholder (3), requirement (3), interface (3), activity (3), system requirement (2), system element (2), system (2), standard (2), stakeholder requirement (2), service (2), safety (2), reliability (2), quality (2), project (2), process (2), port (2), organization (2), need (2), issue (2), interaction (2), functional requirement (2), flexibility (2), and availability (2). The 23 repeating concepts come from a combination of intersections and unions, where a set is represented by each ontology as exemplified in the Venn diagram in Fig. 160. The shaded area in Fig. 160 corresponds to the 23 repeating concepts. The concepts are defined in Table 79 with their respective source. The 474 unique concepts can be compiled by extracting all the concepts from Table 76 and removing the frequency (number in parenthesis minus 1) of the repeating concepts[54].



Ontology 1 ∪ Ontology 2 ∪ Ontology 3 is shaded

Fig. 159 Venn diagram: generalized union between ontology 1, ontology 2 and ontology 3

[53] Relationships will play a role later in integrating the ontology.
[54] This subtraction is intended to keep the repeating concept one time in the core of total unique concepts among the ontologies.



(Ontology 1 ∩ Ontology 2) ∪ (Ontology 1 ∩ Ontology 3) ∪ (Ontology 2 ∩ Ontology 3) is shaded

Fig. 160 Venn diagram: intersections and unions among ontology 1, ontology 2, and ontology 3

From concepts point of view, the ontologies are more complementing than overlapping. This is an interesting finding considering that the ontologies are trying to represent the same scope (i.e., requirement ontology for system life cycle processes). At this point, it is inconclusive to determine which ontology is more representative of the scope of this research; nevertheless, the repeating concepts can be considered constructively as the core of the investigated ontology. The 23 repeating concepts are considered the first consolidation of core concepts for the ontology investigated in this research. These concepts are integrated through relationships in Chapter 4, but after creating taxonomies in Appendix B.

Table 79 Repeating concepts in the ontologies presented by different research groups

#	Concept	German research group	COMPASS research group	Leo van Ruijven
1	Activity	1	1	1
2	Interface	1	1	1
3	Requirement	1	1	1
4	Stakeholder	1	1	1
5	Need	1	1	0
6	Standard	1	1	0
7	Availability	1	0	1
8	Flexibility	1	0	1
9	Functional requirement	0	1	1

10	Interaction	1	0	1
11	Issue	1	0	1
12	Organization	0	1	1
13	Port	0	1	1
14	Process	0	1	1
15	Project	0	1	1
16	Quality	1	0	1
17	Reliability	1	0	1
18	Safety	1	0	1
19	Service	0	1	1
20	Stakeholder requirement	1	0	1
21	System	0	1	1
22	System element	0	1	1
23	System requirement	1	0	1

A.4.2 Relationships

Considering that concepts have been merged from 5 ontologies, the next step is to integrate the concepts using relationships. To achieve this integration, ROM is used (Zeng, 2008). The concepts are integrated in ROM representations using verb phrases previously defined as association relationships. These verb phrases are summarized in Table 78. If the set operation in Fig. 160 is applied for the relationships of the ontologies defined in Table 78, the verb phrases in Table 80 are obtained. The verb phrases in Table 80 shall be used to integrate the concepts into the proposed ontology. As appropriate, the verb phrases in the table can be transformed to base form. Base form enables to define positive active voice arguments (statements). Positive active voice statements (arguments) to integrate concepts and relationships are preferred instead of negative active voice or passive voice ones. Therefore, the verb phrases in Table 80 can be transformed and interpreted from passive to active voice in the ontologies as needed. In addition, the relationships with higher number in the sum column in Table 80 will have possibly a greater chance to be used to relate concepts in the proposed ontology.

Table 80 Verb phrases in association relationships

#	Verb phrases in association /predicate	COMPASS research group	German research group	Leo van Ruijven	Sum
1	consists of	0	0	30	30
2	is derived from	1	0	17	18
3	has property	0	0	14	14
4	has status	0	0	11	11
5	is defined by	0	0	9	9
6	constrains	7	0	0	7
7	is a specification for	0	0	7	7
8	represents the need for	7	0	0	7
9	interacts with	6	0	0	6
10	is identified by	0	0	6	6
11	is instance of	0	0	6	6
12	is performed by	0	0	6	6
13	results in	0	0	6	6
14	describes	5	0	0	5
15	has as output	0	0	5	5
16	is a specialization of	0	0	5	5
17	is described in	0	0	5	5
18	is elicited from	5	0	0	5
19	is realized by	0	0	5	5
20	is related to	5	0	0	5
21	requires	2	2	1	5
22	validates	5	0	0	5
23	causes	0	4	0	4
24	complies with	1	0	3	4
25	conforms to	4	0	0	4
26	has	0	4	0	4
27	instance of	0	4	0	4

28	is base for	0	0	4	4
29	is executed during	4	0	0	4
30	is involved in	0	0	4	4
31	is reason for	0	0	4	4
32	refines	1	3	0	4
33	affects	0	3	0	3
34	defines the type of	3	0	0	3
35	describes the evolution of	3	0	0	3
36	evolves to	0	3	0	3
37	has acceptance criterion	0	0	3	3
38	has issue	0	0	3	3
39	includes	0	3	0	3
40	is input for	0	0	3	3
41	is of type	0	0	3	3
42	is supplemented by	0	0	3	3
43	is threatened by	0	0	3	3
44	is used in	0	0	3	3
45	is validated by	0	0	3	3
46	is verified by	0	0	3	3
47	refers to	0	3	0	3
48	satisfies	1	2	0	3
49	shall be compliant with	0	0	3	3
50	takes place during	0	0	3	3
51	used to check	0	0	3	3
52	accounts for	0	2	0	2
53	assesses the execution of	2	0	0	2
54	can participate in	0	0	2	2
55	collects together	2	0	0	2
56	combines	2	0	0	2
57	concerns	0	0	2	2

58	consumes	2	0	0	2
59	corresponds to	2	0	0	2
60	creates	0	1	1	2
61	describes desired	2	0	0	2
62	describes measured	2	0	0	2
63	describes structure of	2	0	0	2
64	describes the context of	2	0	0	2
65	describes the context of	2	0	0	2
66	exhibits	2	0	0	2
67	has as source	0	0	2	2
68	has author	0	0	2	2
69	has cause	0	0	2	2
70	has consequence if not fulfilled	0	0	2	2
71	is approved by	0	0	2	2
72	is assessed against	2	0	0	2
73	is connected to	2	0	0	2
74	is held at	2	0	0	2
75	is input in	0	0	2	2
76	is managed by	0	0	2	2
77	is output of	0	0	2	2
78	is proposed by	0	0	2	2
79	is quantified in	0	0	2	2
80	is responsible for	2	0	0	2
81	is responsible of	0	0	2	2
82	is the responsibility of	0	0	2	2
83	may be identified by	0	0	2	2
84	performs	0	2	0	2
85	produces	1	1	0	2
86	produces/consumes	2	0	0	2
87	realizes	1	1	0	2

88	results in the generation of	0	0	2	2
89	uses elements from	2	0	0	2
90	visualizes	2	0	0	2
91	can be traced to	1	0	0	1
92	can have as output	0	0	1	1
93	can result in signal	0	0	1	1
94	clarifies	0	0	1	1
95	classifies	1	0	0	1
96	concerns characteristic	0	0	1	1
97	concerns stage	0	0	1	1
98	conflicts	0	1	0	1
99	contains	0	1	0	1
100	contributes in realization of	0	0	1	1
101	control flow	0	1	0	1
102	defines constraints for	1	0	0	1
103	defines context for	1	0	0	1
104	defines requirements in	1	0	0	1
105	defines the delivery of	0	0	1	1
106	depends on	0	1	0	1
107	describes abilities of	1	0	0	1
108	describes interactions between	1	0	0	1
109	describes measured abilities of	1	0	0	1
110	describes the need for	1	0	0	1
111	deviates from	0	0	1	1
112	energy flow	0	1	0	1
113	expands	1	0	0	1
114	exposes	1	0	0	1
115	has as inquiry source	0	0	1	1
116	has consequence	0	0	1	1
117	has effect	0	0	1	1

118	has magnitude	0	0	1	1
119	has milestone	0	0	1	1
120	has output	0	0	1	1
121	has production method	0	0	1	1
122	has remaining risk	0	0	1	1
123	has role	0	1	0	1
124	has scope	0	0	1	1
125	has scope of verification	0	0	1	1
126	has topology	0	0	1	1
127	holds	1	0	0	1
128	influences	0	1	0	1
129	information flow	0	1	0	1
130	interfaces with	1	0	0	1
131	is a failure to perform	0	0	1	1
132	is a state of	0	0	1	1
133	is achieved by	0	0	1	1
134	is an addition to	0	0	1	1
135	is an instance of	0	0	1	1
136	is based on technology	0	0	1	1
137	is connected	0	1	0	1
138	is constrained by	0	0	1	1
139	is contractor for	0	0	1	1
140	is controlled by	0	0	1	1
141	is defined in	0	0	1	1
142	is described by	0	0	1	1
143	is evidence for	0	0	1	1
144	is executed on	0	0	1	1
145	is followed by	0	0	1	1
146	is fulfilled by	0	0	1	1
147	is hierarchically subordinate to	0	0	1	1

148	is initiated by	0	0	1	1
149	is installed as	0	0	1	1
150	is justified by	0	0	1	1
151	is located at	0	0	1	1
152	is lower bound for	0	0	1	1
153	is met by	0	0	1	1
154	is mitigated by	0	0	1	1
155	is needed to deliver	1	0	0	1
156	is part of	0	0	1	1
157	is performed on	0	0	1	1
158	is precondition for	0	0	1	1
159	is principal for	0	0	1	1
160	is raised by	0	0	1	1
161	is realized as	1	0	0	1
162	is represented in	0	0	1	1
163	is required at	1	0	0	1
164	is scheduled in	0	0	1	1
165	is spare part for	0	0	1	1
166	is specified by	0	0	1	1
167	is started at	0	0	1	1
168	is subtype of	0	0	1	1
169	is temporal part of	0	0	1	1
170	is the client for	0	0	1	1
171	is the manufacturers mode for	0	0	1	1
172	is third party for	0	0	1	1
173	is traceable to	1	0	0	1
174	is upper bound for	0	0	1	1
175	leads to	0	1	0	1
176	marks acceptance of	0	0	1	1
177	marks the completion of	0	0	1	1

178	matches	0	1	0	1
179	material flow	0	1	0	1
180	meets	1	0	0	1
181	performs function	0	0	1	1
182	provides	0	1	0	1
183	provides provenance for	1	0	0	1
184	relates to	0	1	0	1
185	requires to deliver	0	0	1	1
186	reveals	0	1	0	1
187	runs	1	0	0	1
188	shows behavior of	1	0	0	1
189	shows the order of execution of	1	0	0	1
190	specifies	0	1	0	1
191	supports	0	0	1	1
192	takes places across	1	0	0	1
193	value flow	0	1	0	1
194	verifies	0	1	0	1
---	TOTAL	121	56	280	457

Appendix B: Ontology design process – creating taxonomies – extending step 8.3

B.1 Introduction

This appendix expands step 8.3 in Chapter 4. This step concerns with creating taxonomies. As taxonomies are equal to ontologies respect to semantic meaning (van Rees, 2003), ontologies must be created to complete the scope and satisfy the requirements defined in Chapter 4. Needed ontologies to complete the scope are identified based on two international standards: ISO/IEC/IEEE (2015) and ISO/IEC/IEEE (2011). These international standards are assumed to be the most definitive sources of information and widely used guidance in the scope of the ontology. The standards correspond to system life processes and requirements engineering respectively.

Considering that ontologies are composed of concepts and relationships, this conceptualization shall be created for the new taxonomies. As a result, the rest of this section discusses concepts and relationships for the proposed ontology in this thesis. In particular, Section B.2.1 discusses the creation of concepts for the proposed ontology, and Section B.2.2 discusses the creation of relationships for the proposed ontology.

B.2 Step 8.3: Create taxonomies

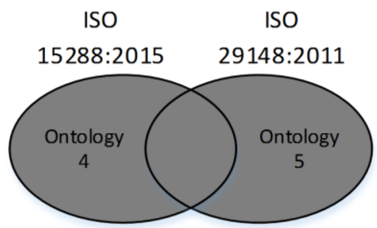
B.2.1 Creation of concepts for the proposed ontology

The international standards ISO/IEC/IEEE (2015) and ISO/IEC/IEEE (2011) present together 87 concepts (aka terms or definitions) to be the foundation to identify needed ontologies. ISO/IEC/IEEE (2015) presents 54 concepts. ISO/IEC/IEEE (2011) present 33 concepts. These concepts are defined in Table 81.

Table 81 Concepts from ISO/IEC/IEEE (2015) and ISO/IEC/IEEE (2011)

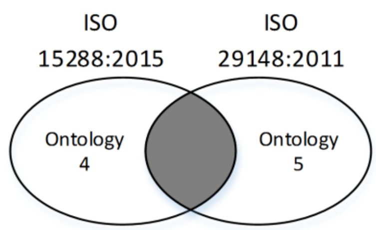
ISO/IEC/IEEE (2015) - ISO 15288:2015		ISO/IEC/IEEE (2011) - ISO 29148:2011
Acquirer Acquisition Activity Agreement Architecture Architecture framework Architecture view Architecture viewpoint Audit Baseline Concept of operations Concern Configuration item Customer Design Design Design characteristic Enabling system Environment Facility Incident Information item Life cycle Life cycle model Operational concept Operator Organization Party Problem Process	Process purpose Product Project Quality assurance Quality characteristic Quality management Requirement Resource Retirement Risk Security Service Stage Stakeholder Supplier System System element System-of-interest Systems engineering Task Trade-off User Validation Verification	Acquire Attribute Baseline Concept of operations Condition Constraint Customer Derived requirement Developer Document Human system integration Level of abstraction Mode Operational concept Operational scenario Operator Requirement Requirements elicitation Requirements engineering Requirements management Requirements traceability matrix Requirements validation Requirements verification Software requirements specification Stakeholder State Supplier System-of-interest System requirements specification Trade-off User Validation Verification

From the 87 concepts in Table 81, there are 73 unique concepts between the standards, and 14 repeating (overlapping concepts). The 73 unique concepts are the shaded area in the Venn diagram in Fig. 161. This shaded area represents the union between the concepts in ISO 15288:2015 and ISO 29148:2011. Repeating concepts correspond to the shaded area in the Venn diagram in Fig. 162. The shaded region is the intersection between the concepts in ISO 15288:2015 and ISO 29148:2011. The repeating concepts and unique concepts are defined in Table 82.



Ontology 4 ∪ Ontology 5 is shaded

Fig. 161 Venn diagram: union between ontology 4 and ontology 5



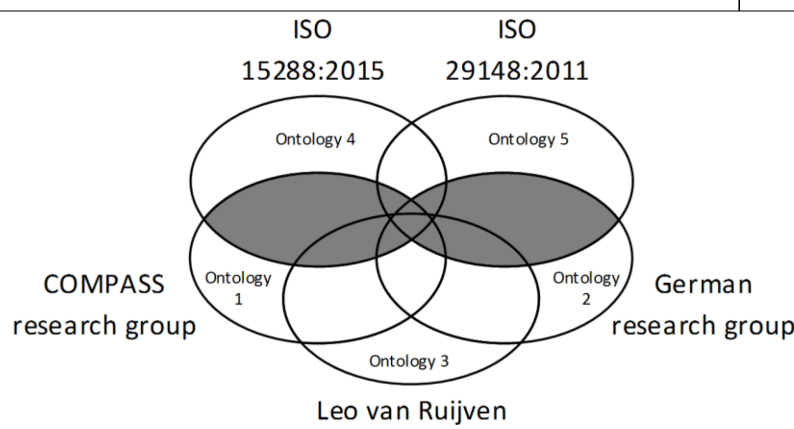
Ontology 4 ∩ Ontology 5 is shaded

Fig. 162 Venn diagram: intersection between ontology 4 and ontology 5

From the 73 unique concepts in Table 82 (i.e., Fig. 161), only 26 concepts appeared in the 501 concepts of the investigated ontologies defined in Table 12 in Appendix A; reaching a ratio of 5.2% (i.e., 26 out 501). These 26 concepts are represented in the shaded area in the Venn diagram in Fig. 163. Table 83 defines the 26 concepts, their total appearing frequency, and the ontology where the concepts appear. Table 83 indicates that the COMPASS research group used more concepts in their ontologies related to ISO/IEC/IEEE (2015) and ISO/IEC/IEEE (2011); therefore, the COMPASS research group has created the most representative requirement ontology within the scope of defined concepts in the international standards. The COMPASS research group is followed by Leo van Ruijven, and finally by the German research group. From Table 83, it is also interesting to highlight that that from the 501 unique concepts defined by the research groups in Table 12 in Appendix A, only 26 concepts overlap with ISO/IEC/IEEE (2015) and ISO/IEC/IEEE (2011).

Table 82 Unique and repeating concepts from ISO/IEC/IEEE (2015) and ISO/IEC/IEEE (2011)

Unique concepts	Repeating concepts
Acquirer, Acquisition, Activity, Agreement, Architecture, Architecture framework, Architecture view, Architecture viewpoint, Attribute, Audit, Baseline, Concept of operations, Concern, Condition, Configuration item, Constraint, Customer, Derived requirement, Design noun, Design verb, Design characteristic, Developer, Document, Enabling system, Environment, Facility, Human system integration, Incident, Information item, Level of abstraction, Life cycle, Life cycle model, Mode, Operational concept, Operational scenario, Operator, Organization, Party, Problem, Process, Process purpose, Product, Project, Quality assurance, Quality characteristic, Quality management, Requirement, Requirements elicitation, Requirements engineering, Requirements management, Requirements traceability matrix, Requirements validation, Requirements verification, Resource, Retirement, Risk, Security, Service, Software requirements specification, Stage, Stakeholder, State, Supplier, System, System element, System requirements specification, System-of-interest, Systems engineering, Task, Trade-off, User, Validation, Verification	Acquirer, Baseline, Concept of operations, Customer, Operational concept, Operator, Requirement, Stakeholder, Supplier, System-of-interest, Trade-off, User, Validation, Verification



(Ontology 4 ∩ Ontology 1) ∪ (Ontology 4 ∩ Ontology 2) ∪ (Ontology 4 ∩ Ontology 3) ∪ (Ontology 5 ∩ Ontology 1) ∪ (Ontology 5 ∩ Ontology 2) ∪ (Ontology 5 ∩ Ontology 3) is shaded

Fig. 163 Venn diagram: some intersections and unions among the ontologies

Table 83 Concepts in ISO/IEC/IEEE (2015)[55] and ISO/IEC/IEEE (2011)[56] and their number of times appearing in the investigated ontologies

#	Concept	Source	Total appearing times	COMPASS research group	German research group	Leo van Ruijven
1	Activity	ISO 15288	3	1	1	1
2	Requirement	ISO 15288	3	1	1	1
3	Stakeholder	ISO 15288	3	1	1	1
4	Organization	ISO 15288	2	1	0	1
5	Process	ISO 15288	2	1	0	1
6	Project	ISO 15288	2	1	0	1
7	Service	ISO 15288	2	1	0	1
8	System	ISO 15288	2	1	0	1
9	System element	ISO 15288	2	1	0	1
10	Architecture	ISO 15288	1	1	0	0
11	Attribute	ISO 29148	1	0	1	0
12	Concern	ISO 15288	1	1	0	0
13	Customer	ISO 15288	1	0	1	0
14	Document	ISO 29148	1	0	0	1
15	Enabling system	ISO 15288	1	1	0	0
16	Environment	ISO 15288	1	0	0	1
17	Life cycle	ISO 15288	1	1	0	0
18	Life cycle model	ISO 15288	1	1	0	0
19	Party	ISO 15288	1	0	0	1
20	Product	ISO 15288	1	1	0	0
21	Quality management	ISO 15288	1	0	1	0
22	Resource	ISO 15288	1	1	0	0

[55] ISO 15288 is used interchangeably with this citation with the purpose of reducing string used in this and subsequent tables.
[56] ISO 29148 is used interchangeably with this citation with the purpose of reducing string used in this and subsequent tables.

23	Risk	ISO 15288	1	0	0	1
24	Stage	ISO 15288	1	1	0	0
25	State	ISO 29148	1	0	1	0
26	User	ISO 15288	1	0	1	0
---	Total	----------	38	17	8	13

Considering that the 5.2% ratio given by the combination of intersections and unions (represented in the operation in Fig. 163 resulting in Table 83) of the concepts in ISO/IEC/IEEE (2015), ISO/IEC/IEEE (2011), and Table 12 in Appendix A is low; a requirement ontology shall include other concepts to be more representative of the domain of interest. To achieve that goal, the 26 concepts obtained from the operation in Fig. 163 can be complemented with other repeating concepts. The complementing repeating concepts belong to two groups: 1) 14 repeating concepts from the international standards defined in Table 82 (represented in the operation in Fig. 162), and 2) 23 repeating concepts from the investigated ontologies defined in Table 15 in Appendix A (represented in the operation in the left side of Fig. 164). Thus, the minimum concepts in the ontology are given by the generalized union of concepts represented in Fig. 164. The resulting generalized union is summarized in Fig. 165, which can be interpreted as the resulting concepts must be in at least two ontologies to be part of the proposed core ontology. The resulting generalized union of concepts is defined in Table 84, including 50 concepts. The table also traces the origin of the 50 concepts. The 50 concepts are defined as the core concepts to be included in the ontology. The 50 concepts are expected to create a balance and constructive approach using concepts from international standards and international researchers.

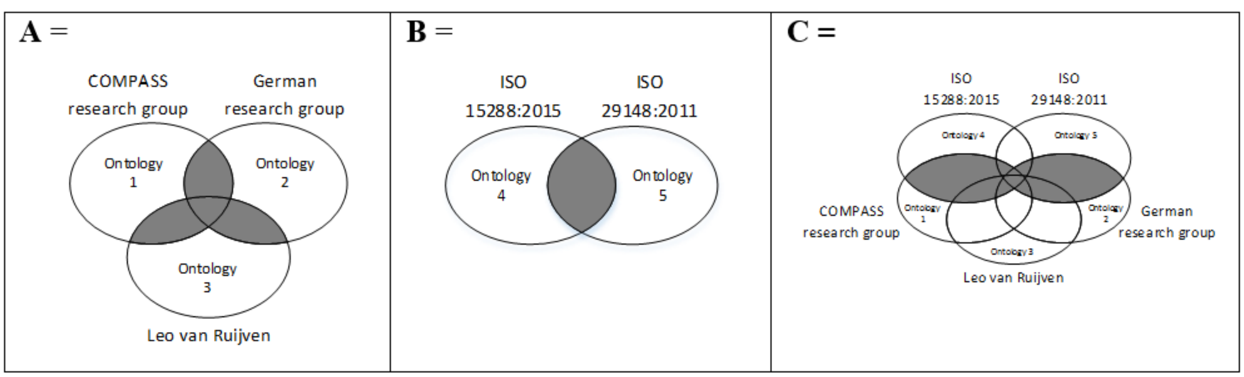


Fig. 164 Proposed ontology: generalized union (A ∪ B ∪ C)

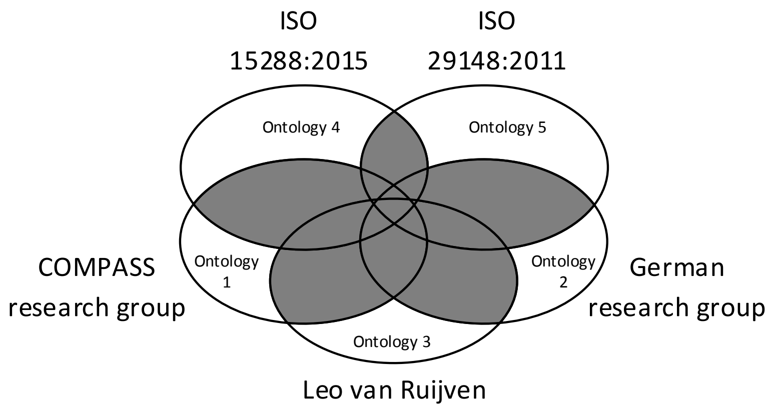


Fig. 165 Proposed ontology: resulting generalized union (A ∪ B ∪ C) from Fig. 164

Table 84 Concepts for a requirement ontology to guide the analysis of system life cycle processes

#	Concept	COMPASS research group	German research group	Leo van Ruijven	ISO 15288	ISO 29148	Sum
1	Acquirer	0	0	0	1	1	2
2	Activity	1	1	1	1	0	4
3	Architecture	1	0	0	1	0	2
4	Attribute	0	1	0	0	1	2
5	Availability	0	1	1	0	0	2
6	Baseline	0	0	0	1	1	2
7	Concept of operations	0	0	0	1	1	2
8	Concern	1	0	0	1	0	2
9	Customer	0	1	0	1	1	3
10	Document	0	0	1	0	1	2
11	Enabling system	1	0	0	1	0	2
12	Environment	0	0	1	1	0	2
13	Flexibility	0	1	1	0	0	2
14	Functional requirement	1	0	1	0	0	2
15	Interaction	0	1	1	0	0	2
16	Interface	1	1	1	0	0	3
17	Issue	0	1	1	0	0	2

18	Life cycle	1	0	0	1	0	2
19	Life cycle model	1	0	0	1	0	2
20	Need	1	1	0	0	0	2
21	Operational concept	0	0	0	1	1	2
22	Operator	0	0	0	1	1	2
23	Organization	1	0	1	1	0	3
24	Party	0	0	1	1	0	2
25	Port	1	0	1	0	0	2
26	Process	1	0	1	1	0	3
27	Product	1	0	0	1	0	2
28	Project	1	0	1	1	0	3
29	Quality	0	1	1	0	0	2
30	Quality management	0	1	0	1	0	2
31	Reliability	0	1	1	0	0	2
32	Requirement	1	1	1	1	1	5
33	Resource	1	0	0	1	0	2
34	Risk	0	0	1	1	0	2
35	Safety	0	1	1	0	0	2
36	Service	1	0	1	1	0	3
37	Stage	1	0	0	1	0	2
38	Stakeholder	1	1	1	1	1	5
39	Stakeholder requirement	0	1	1	0	0	2
40	Standard	1	1	0	0	0	2
41	State	0	1	0	0	1	2
42	Supplier	0	0	0	1	1	2
43	System	1	0	1	1	0	3
44	System element	1	0	1	1	0	3
45	System requirement	0	1	1	0	0	2
46	System-of-interest	0	0	0	1	1	2
47	Trade-off	0	0	0	1	1	2
48	User	0	1	0	1	1	3

49	Validation	0	0	0	1	1	2
50	Verification	0	0	0	1	1	2
---	TOTAL	22	20	25	33	17	117

B.2.2 Creation of relationships for the proposed ontology

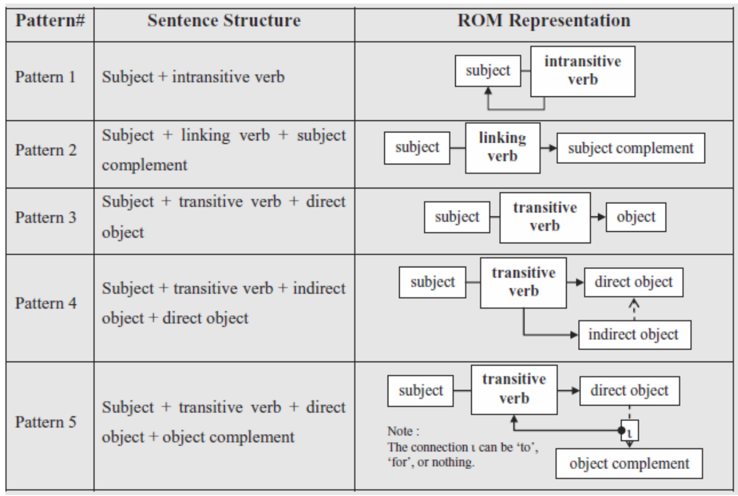
Relationships for the proposed ontology adopt a less restrictive approach as for concepts. At this point of development, all the relationships defined in Appendix A (i.e., Section (A.4.2)) are considered sufficient for relating the concepts in Table 84. If the list is not sufficient, verbs from the international standards (ISO/IEC/IEEE, 2011, 2015) shall be extracted. More specifically, these verbs can be extracted from the proposed definitions employed in the international standards.

Appendix C: Ontology design process – partial list of statements in the core ontology

C.1 Introduction

This appendix presents the list of statements defined in the third lightest ontology (Section C.2) and a partial list of statement in the proposed core ontology (Section C.3). The list of statement in the proposed core ontology can be obtained following the logic used to obtain the statements in Table 85 and Table 86. The logic suggests that a statement representing a necessary condition derives sufficient conditions. Necessary conditions are obtained from the ontologies by identifying patterns in English sentences. Such patterns are summarized in Fig. 166, defined using ROM elements. A statement representing a necessary condition can be created starting from any concept in the ontology. For each concept, a subject-verb path can be selected as desired or needed to initiate the necessary condition. Sufficient conditions also satisfy the syntax of the sentence patterns. The logic to identify sufficient conditions in the ontologies is to follow the graph until closing and reaching to the necessary condition used as a point of reference. The path for creating sufficient conditions until returning to the necessary conditions follows a causal sequence represented by sentence patterns implicit in the ontology. Cause and effect in causal reasoning allows to define causal sequences (aka chain of events) (i.e., A causes B, B causes C, C causes D, and D causes E, where E is the final effect or outcome) (Copi & Cohen, 1998, p. 498).

The rest of the appendix defines the identified statements in the third lightest ontology (Section C.2) and the proposed core ontology (Section C.3).



Pattern#	Sentence Structure	ROM Representation
Pattern 1	Subject + intransitive verb	subject; intransitive verb
Pattern 2	Subject + linking verb + subject complement	subject; linking verb; subject complement
Pattern 3	Subject + transitive verb + direct object	subject; transitive verb; object
Pattern 4	Subject + transitive verb + indirect object + direct object	subject; transitive verb; direct object; indirect object
Pattern 5	Subject + transitive verb + direct object + object complement	subject; transitive verb; direct object; object complement; Note : The connection ι can be 'to', 'for', or nothing.

Fig. 166 Sentence patterns of the technical English (Zeng, 2008)

C.2 List of statement in the third lightest ontology

This section of the appendix defines the necessary and sufficient conditions that can be inferred from the third lightest ontology. These conditions are defined in Table 85.

Table 85 List of statements in the third lightest ontology

#	Statement and relationships (red) – Necessary (N) and sufficient (S) conditions	Source of relationship in list in Appendix A (Section A.4.2)
1	Stakeholder defines requirement during activity (N). Activity creates process (S). Process defines activity (S). Requirement defines activity (S). Activity defines requirement (S). Requirement defines system (N). System combines system element through interface (S). Interface combines system element (S). System element interacts with system (S). System element realizes service (S). System realizes service (S). Service realizes activity (S).	5 60 5 5 5 5 56 56 9 19 19 19

	System realizes activity (S). Activity creates process (S). Process defines activity (S). Activity defines requirement (S). Requirement defines stakeholder (S).	19 60 5 5 5
2	Stakeholder manages activity (N). Activity creates process (S). Process defines activity (S). Activity defines requirement (S). Requirement defines activity (S). Requirement defines stakeholder (S).	76 60 5 5 5 5
3	Requirement defines activity (N). Activity creates process (S). Process defines activity (S). Activity defines requirement (S).	5 60 5 5
4	Stakeholder is[57] organization, customer, and user (N). Organization is stakeholder (S). Customer is stakeholder (S). User is stakeholder (S).	5 5 5 5
5	Stakeholder manages process (N). Process defines activity (S). Activity creates process (S). Activity defines requirement (S). Requirement defines stakeholder (S).	76 5 60 5 5
6	Stakeholder manages project (N). Project defines process (S). Process defines activity (S). Activity creates process (S). Activity defines requirement (S).	76 5 5 60 5

[57] The verb "is" is considered equal as "is defined by" listed as number 5 in Table 80.

	Requirement defines stakeholder (S).	5
7	Requirement defines system (N). System combines system element through interface (S). Interface combines system element (S). System element interacts with system (S). System element realizes service (S). System realizes service (S). Service realizes activity (S). System realizes activity (S). Activity creates process (S). Process defines activity (S). Activity defines requirement (S).	5 56 56 9 19 19 19 19 60 5 5
8	Requirement defines service (N). Service realizes activity (S). Activity defines requirement (S).	5 19 5
9	Requirement defines system element (N). System element interacts with system (S). System combines system element through interface (S). Interface combines system element (S). System element realizes service (S). System realizes activity (S). System realizes service (S). Service realizes activity (S). Activity defines requirement (S).	5 9 56 56 19 19 19 19 5
10	Requirement defines interface (N). Interface combines system element (S). System element interacts with system (S). System combines system element through interface (S). System realizes activity (S). System realizes service (S). System element realizes service (S).	5 56 9 56 19 19 19

	Service realizes activity (S). Activity defines requirement (S).	19 5

C.3 Partial list of statement in the proposed core ontology

This section of the appendix defines the necessary and sufficient conditions that can be inferred from the proposed core ontology. These conditions are defined in in the partial list of statements in Table 86. The represented examples in the table are expected to illustrate the underlying reasoning to create necessary and sufficient conditions. The examples cover several statements in the ontology. The remaining statements can be obtained by developing necessary and sufficient conditions for the system life cycle process concept, but until now it is assumed that the goal of the ontology has been satisfied. This assumption is acknowledged by the fact that further research is needed to understand and evaluate necessary and sufficient conditions obtained from the ontology. More specifically, further research needs to be done to define and understand the boundaries of necessary and sufficient conditions from the ROM representation. Such boundaries shall be investigated using logical properties such as idempotent relation, commutative relation, associative relation, transitive relation, distributive relation, and structure operation (Zeng, 2002, 2004a). Understanding and defining the boundaries can come from specific system life cycle analyses (INCOSE, 2004, pp. 154-178), aka ilities or specialty engineering (INCOSE, 2015, pp. 211-241). Those analyses can be broken down into a number of competency questions that shall be answered from the ontology at the desired level of details. Such investigation can support automation to achieve the desired understanding and control of necessary and sufficient conditions.

Table 86 Partial list of statements in the core ontology

#	Statement and relationships (red) – Necessary (N) and sufficient (S) conditions	Source of relationship in list in Appendix A (Section A.4.2)
1	Stakeholder defines requirement during activity in document (N). Document defines requirement during activity. Activity creates process (S). Process defines activity (S).	5 5 60 5

	Requirement defines activity (S).	5
	Activity defines requirement (S).	5
	Requirement defines system-of-interest (S).	5
	Requirement defines enabling system (S).	5
	Requirement defines baseline (S).	5
	Requirement defines stakeholder requirement (S).	5
	Requirement defines system requirements (S).	5
	Requirement defines functional requirements (S).	5
	Requirement defines system (S).	5
	System has operator (S).	26
	Operator is stakeholder (S).	5
	Stakeholder derives need (S).	2
	Stakeholder describes need (S).	14
	Operator describes issue (S).	14
	Operator describes concern (S).	14
	Concern defines need (S).	5
	Issue defines need (S).	5
	Need defines requirement during activities (S).	5
	Operator control system (S).	101, 140
	System satisfies baseline (S).	48
	System realizes service (S).	19
	System combines system element through interface (S).	56
	Interface combines system element (S).	56
	Interface satisfies baseline (S).	48
	Interface creates interaction (S).	60
	Interaction constrains interface (S).	6
	Interaction constrains port (S).	6
	Port is interface (S).	5
	Interaction satisfies baseline (S).	48
	System element interacts with system (S).	9
	System element realizes service (S).	19

	System element realizes product (S).	19
	Product satisfies baseline (S).	48
	Service satisfies baseline (S).	48
	Service realizes activity (S).	19
	System realizes activity (S).	19
	Activity creates process (S).	60
	Process defines activity (S).	5
	Activity defines requirement (S).	5
	Requirement defines stakeholder (S).	5
	Requirement has attribute (S).	26
	Attribute defines safety, availability, flexibility, reliability, and others (S).	5
	Attribute is base for verification (S).	28
	Verification checks quality (S).	51
	Quality has attribute (S).	26
	Quality meets requirement (S).	180
	Requirement defines architecture (S).	5
	Architecture describes system (S).	14
	Architecture describes interface (S).	14
	Architecture describes system-of-interest (S).	14
	System-of-interest realizes in environment (S).	19
	Environment constrains system (S).	6
	Environment constrains life cycle (S).	6
	Life cycle evolves system-of-interest (S).	36
	Life cycle evolves in stage (S).	36
	Stage evolves life cycle (S).	36
	Environment constrains architecture (S).	6
	Architecture describes life cycle (S).	14
	Architecture describes enabling systems (S).	14
	Enabling system is system (S).	5
		191

	Enabling system supports system of interest during stage of life cycle (S).	14
	Architecture describes baseline (S).	166, 190
	Baseline specifies quality (S).	180
	Baseline meets requirement (S).	5
	System requirement is requirement (S).	5
	Functional requirement is requirement (S).	5
	Stakeholder requirement is requirement (S).	
2	Stakeholder manages activity (N).	76
	Activity creates process (S).	60
	Process consumes resources (S).	58
	Resource is base for process (S).	28
	Process defines activity (S).	5
	Activity defines requirement (S).	5
	Requirement defines activity (S).	5
	Requirement defines stakeholder (S).	5
3	Requirement defines activity (N).	5
	Activity creates process (S).	60
	Process consumes resources (S).	58
	Resource is base for process (S).	28
	Process defines activity (S).	5
	Activity defines requirement (S).	5
4	Stakeholder is organization, customer, user, acquirer, supplier, and operator (N).	5
	Organization describes issue (S).	14
	Organization describes concern (S).	14
	Organization is party (S).	5
	Organization defines concept of operation (S).	5
	Organization defines operational concept (S).	5
	Operational concept is part of concept of operation (S).	5
	Concept of operation defines need (S).	5

	Concept of operation constrains validation (S).	6
	Operational concept constrains validation (S).	6
	Validation is verification for operational concept (S).	5
	Validation is verification for concept of operation (S).	5
	Validation has state (S).	26
	State is base for verification (S).	28
	State checks quality (S).	51
	State checks attribute (S).	51
	Concept of operation creates risk (S).	60
	Operational concept creates risk (S).	60
	Risk affects quality (S).	33
	Quality meets requirement (S).	180
	Quality has attributes (S).	26
	Customer describes issue (S).	14
	Customer describes concern (S).	14
	Customer is party (S).	5
	User describes issue (S).	14
	User describes concern (S).	14
	User is party (S).	5
	Acquirer describes issue (S).	14
	Acquirer describes concern (S).	14
	Acquirer is party (S).	5
	Supplier describes issue (S).	5
	Supplier describes concern (S).	5
	Supplier is party (S).	5
	Supplier supplements product (S).	42
	Supplier supplements service (S).	42
	Operator describes issue (S).	14
	Operator describes concern (S).	14
	Operator is party (S).	5
	Operator controls system (S).	101, 140

	Issue defines need (S).	5
	Concern defines need (S).	5
	Need defines requirement during activity (S).	5
	Process consumes resource (S).	58
	Resource is base for process (S).	28
	Requirement has attribute (S).	26
	Attribute defines safety (S).	5
	Attribute defines availability (S).	5
	Attribute defines flexibility (S).	5
	Attribute defines reliability (S).	5
	Attribute defines others (S).	5
	Attribute is base for verification (S).	28
	Verification checks attribute (S).	51
	Verification checks quality (S).	51
	Requirement defines stakeholder requirement (S).	5
	Requirement defines system requirement (S).	5
	Requirement defines functional requirement (S).	5
	Stakeholder requirement is requirement (S).	5
	System requirement is requirement (S).	5
	Functional requirement is requirement (S).	5
	Requirement defines baseline (S).	5
	Baseline specifies quality (S).	166, 190
	Baseline meets requirement (S).	180
	Requirement defines system (S).	5
	System satisfies baseline (S).	48
	System realizes service (S).	19
	System combines system element through interface (S).	55
	Interface combines system element (S).	55
	Interface satisfies baseline (S).	48
	Interface creates interaction (S).	60
	Interaction constrains interface (S).	6

	Interaction constrains port (S).	6
	Port is interface (S).	5
	Interaction satisfies baseline (S).	48
	System element interacts with system (S).	9
	System element realizes service (S).	19
	System element realizes product (S).	19
	Product satisfies baseline (S).	48
	Service satisfies baseline (S).	48
	Service realizes activity (S).	19
	System realizes activity (S).	19
	Activity creates process (S).	30
	Process defines activity (S).	5
	Activity defines requirement (S).	5
	Requirement defines architecture (S).	5
	Architecture describes system (S).	14
	Architecture describes interface (S).	14
	Architecture describes system-of-interest (S).	14
	System-of-interest realizes in environment (S).	19
	Environment constrains system (S).	6
	Environment constrains life cycle (S).	6
	Life cycle evolves system-of-interest (S).	36
	Life cycle evolves in stage (S).	36
	Stage evolves life cycle (S).	36
	Environment constrains architecture (S).	6
	Architecture describes life cycle (S).	14
	Architecture describes enabling systems (S).	14
	Enabling system is system (S).	5
	Enabling system supports system of interest during stage of life cycle (S).	191
	Architecture describes baseline (S).	14
	Requirement defines enabling system (S).	5

	Requirement defines system-of-interest (S).	5
	Party manages trade-offs through activity (S).	76
	Party manages standard through activity (S).	76
	Standard specifies attribute in verification (S).	166, 190
	Standard specifies process (S).	166, 190
	Standard is document (S).	5
	Document defines requirement during activity (S).	5
	Trade-off affects stakeholder (S).	33
	Organization is stakeholder (S).	5
	Customer is stakeholder (S).	5
	User is stakeholder (S).	5
5	Stakeholder manages quality management through activity (N).	76
	Quality management has process (S).	26
	Process consumes resources (S).	58
	Resource is base for process (S).	28
	Process defines activity (S).	5
	Activity defines requirement (S).	5
	Requirement defines stakeholder (S).	5

Appendix D: Case study 1 - Total quality management system guideline development using Environment-Based Design for area development planning

D.1 Introduction

The purpose of this appendix is to document additional content to the case study in Chapter 5. In particular, the appendix documents additional content related to conflict identification. The additional content can be found in Section D.2.

D.2 Conflict identification

Conflicts arise after conducting a systematic gap evaluation between the TQMS guideline (requirements in Table 30) to be designed and current ADP's environment components (i.e., workflows from Fig. 45 to Fig. 56). Table 87 to Table 96 show the systemic gap evaluations. Table 87 to Table 96 follows the proposed structure in Table 32, but the ISOR (i.e., ISO 9001:2008 requirements column) was moved to the caption of the table. Thus, Table 87 to Table 96 corresponds to requirements 1 to 10 (i.e., $ISOR_1$ to $ISOR_{10}$) from Table 30 and Table 31 respectively.

Table 87 Gap evaluation: ISOR 1 – General requirements for the QMS: determine the processes needed for the QMS and their application throughout ADP

ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders	ADP's supporting documents	Gap evaluations
1. Management responsibility	General supervisor (GS) tasks	GS	General supervisor, ADP workflows in the Environment Analysis (EA) report	
2. Resource management	General supervisor (GS) tasks	GS		
3. Service realization	GS tasks; groups members (GM) tasks	GS, GM	General supervisor, ADP, members workflows in the EA report	
4. Measurement		GS, GM		Metrics shall be created to evaluate the effectiveness of the GS and GM tasks towards the quality policy. It shall also be determined how and how often to measure the created metrics
5. Analysis		GS, GM		A process-method shall be created to analyze the effectiveness of the measurement results (see gap evaluation in ISOR 1.4[58]).
6. Improvement		GS, GM		A process-method shall be created to improve continuously the effectiveness of the GS and GM tasks effectiveness towards the quality policy based on the analysis (see gap evaluation in ISOR 1.5).

Table 88 Gap evaluation: ISOR 2 – General requirements for the QMS: determine sequence and interaction of the processes

ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders	ADP's supporting documents	Gap evaluations
1. Management responsibility	GS, ADP workflows	GS	General supervisor, ADP workflows in the EA report	
2. Resource management	GS, ADP workflows		General supervisor, ADP, members	

[58] The notation ISOR 1.4 is composed of the requirement (1) and the sub-requirement (4). This notation will be used hereafter in the table when necessary.

			workflows in the EA report	
3. Service realization	GS, ADP, and GM workflows	GS, GM	General supervisor, ADP, members workflows in the EA report	
4. Measurement		GS, GM		Metrics shall be created to evaluate the sequence and interactions of processes. It shall also be determined how and how often to measure the created metrics.
5. Analysis		GS, GM		A process-method shall be created to analyze the sequence and interactions of processes (see gap evaluation in ISOR 2.4).
6. Improvement		GS, GM		A process-method shall be created to improve continuously the sequence and interactions of processes based on the analysis (see gap evaluation in ISOR 2.5). Any supporting document needed shall be created/updated.

Table 89 Gap evaluation: ISOR 3 – General requirements for the QMS - determine the criteria and methods needed to ensure that both the operation and control of the processes are effective

ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders	ADP's supporting documents	Gap evaluations
1. Management responsibility	Work plans tracking (follow up progress); members' work-life balance; members motivation; members capability; maintain knowledge and skills identified in GS workflow	GS, GM	General supervisor, ADP workflows in the EA report	
2. Resource management	Staff career development: Members improvements in career development; members feedback	GS, GM	General supervisor, ADP, members workflows in the EA report	
3. Service realization	High quality projects; stakeholders satisfaction; compliance with stakeholders' requirements; compliance with Drainage services EMS ISO 14001:2004, 10 years approval to operate and The City of Edmonton Drainage Services Master Plan 2004 –	GS, GM	General supervisor, ADP, members workflows in the EA report; EA report	

	2014 Implementation and strategies requirements shall be included in the ISO 9001:2008 requirements; maintain knowledge and skills identified in members workflows			
4. Measurement		GS, GM		Metrics (KPIs) should be created to evaluate the effectiveness of the operation and control of the GS and GM tasks
5. Analysis		GS, GM		A process-method shall be created to analyze the effectiveness of the operation and control of the GS and GM tasks (see gap evaluation in ISOR 3.4)
6. Improvement		GS, GM		A process-method shall be created to improve continuously the effectiveness of the operation and control of GS and GM tasks based on the analysis (see gap evaluation in ISOR 3.5)

Table 90 Gap evaluation: ISOR 4 – General requirements for the QMS: ensure the availability of resources and information necessary to support the operation and monitoring of these processes

ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders	ADP's supporting documents	Gap evaluations
1. Management responsibility	General supervisor (GS) develops budget plans including operation and capital to conduct work; GS mentors and coaches for staff career development; GS deals with provincial regulations; GS is board of direction of NSWA, AWC, and other city-wide strategy commits	GS	General supervisor, ADP workflows in the EA report	

2. Resource management	Refer to management activities to ensure the availability of resources and information	GS	General supervisor, ADP, members workflows in the EA report	
3. Service realization	Team leaders (TL) and groups members (GM) deal with inquiries; they maintain knowledge; they act as drainage representative for special projects; training; research	GS, GM	General supervisor, ADP, members workflows in the EA report	
4. Measurement		GS, GM		Metrics should be created to evaluate the effectiveness of the availability of resources and information to support the operation and monitoring of the GS and GM tasks. It shall also be determined how and how often to measure the created metrics
5. Analysis		GS, GM		A process-method shall be created to analyze the effectiveness of the availability of resources and information to support the operation and monitoring of the GS and GM tasks (see gap evaluation in ISOR 4.4)
6. Improvement		GS, GM		A process-method shall be created to improve continuously the effectiveness of the availability of resources and information to support the operation and monitoring of the GS and GM tasks based on the analysis (see gap evaluation in ISOR 4.5)

Table 91 Gap evaluation: ISOR 5 – General requirements for the QMS: monitor, measure where applicable, and analyze these processes

ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders	ADP's supporting documents	Gap evaluations
1. Management responsibility	Work plans tracking (follow up progress); members' work-life balance; members motivation; members capability; maintain knowledge and skills identified in GS workflow	GS, GM	General supervisor, ADP workflows in the EA report	From GM interviews, it was found that workload/task distribution shall be balanced and redefined; and staff motivation shall be improved
2. Resource management	Staff career development: Members improvements in career development; members feedback	GS, GM	General supervisor, ADP, members workflows in the EA report	From the GM interviews, it was found that GM are requesting training for technical position, communication improvement about roles and responsibilities, and hiring more staff
3. Service realization	High quality projects; stakeholders satisfaction; compliance with stakeholders' requirements; compliance with Drainage services EMS ISO 14001:2004, 10 years approval to operate and The City of Edmonton Drainage Services Master Plan 2004 – 2014 Implementation and strategies requirements shall be included in the ISO 9001:2008 requirements; maintain knowledge and skills identified in members workflows	GS, GM	General supervisor, ADP, members workflows in the EA report; EA report	Issues and suggestions in GM and external stakeholder's interviews shall be addressed.
4. Measurement		GS, GM		Metrics should be created to evaluate the effectiveness of the monitoring, measuring and analyzing processes of the GS and GM tasks. It shall also be

				determined how and how often to measure the created metrics.
5. Analysis		GS, GM		A process-method shall be created to analyze the effectiveness of the measurement results (see gap evaluation in ISOR 5.4).
6. Improvement		GS, GM		A process-method shall be created to improve continuously the effectiveness of the monitoring, measuring and analyzing processes of the GS and GM tasks based on the analysis (see gap evaluation in ISOR 5.5)

Table 92 Gap evaluation: ISOR 6 – General requirements for the QMS - determine the processes needed for the QMS and their application throughout ADP

ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders	ADP's supporting documents	Gap evaluations
1. Management responsibility	GS mentors and coaches to members; GS coordinates groups tasks with other groups and sections; staff career development	GS, GM		All the issues in ISOR 5.1 shall be addressed. Any supporting document needed shall be created/updated
2. Resource management	GS mentors and coaches to members; GS develops budget for maintaining operational capability	GS, GM		All the issues in ISOR 5.2 shall be addressed. Any supporting document needed shall be created/updated
3. Service realization	Project amendments, training	GS, GM		All the issues in ISOR 5.3 shall be addressed. Any supporting document needed shall be created/updated
4. Measurement		GS, GM		Metrics should be created to evaluate the effectiveness of the implementing actions processes of the GS and GM tasks. It shall also be determined how and how often to measure the created metrics. Any supporting document needed shall be created/updated

5. Analysis		GS, GM		A process-method shall be created to analyze the effectiveness of the measurement results (see gap evaluation in ISOR 6.4). Any supporting document needed shall be created/updated
6. Improvement		GS, GM		A process-method shall be created to improve continuously the effectiveness of the implementing actions processes of the GS and GM tasks based on the analysis (see gap evaluation in ISOR 6.5). Any supporting document needed shall be created/updated

Table 93 Gap evaluation: ISOR 7 – Documentation requirements for QMS - general

ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders	ADP's supporting documents	Gap evaluations
1. Documented statements of a quality policy and quality objectives		GS, GM		A quality policy and objectives need to be created.
2. A quality manual		Refer to the quality manual (ISOR 8)	Refer to the quality manual (ISOR 8)	Refer to the quality manual (ISOR 8)
3. Documented procedures and records required by ISO 9001:2008				Refer to ISOR 8.2 to find the documented procedures required by ISO 9001:2008. The 21 records required shall be created.
4. Documents, including records, determined by ADP to be necessary to ensure the effective planning, operation and control of the processes				These documents and records shall be determined after generating solution to previous ISORs.

Table 94 Gap evaluation: ISOR 8 – Documentation requirements for QMS - quality manual

ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders	ADP's supporting documents	Gap evaluations
1. Scope of the QMS	The current QMS covers ADP processes. Refer to ADP general workflow and ADP's general supervisor workflow in the EA report	GS, GM		A document containing the scope of the QMS system shall be created.
2. Documented procedures established for the QMS, or references to them	Refer to the workflows in the EA report	GS, GM	General supervisor, ADP, members workflows in the EA report	Control of documents, control of records, internal audits, control of nonconforming products, corrective actions and preventive actions documented procedures shall be created.
3. A description of the interaction between the processes of the QMS	Refer to the workflows in the EA report	GS, GM	General supervisor, ADP, members workflows in the EA report	Organizational chart and workflows already show interaction between the processes in the QMS; however, it depends on the GS and GM how detailed they want to demonstrate the interactions between the processes.

Table 95 Gap evaluation: ISOR 9 – Documentation requirements for QMS - control of documents

ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders	ADP's supporting documents	Gap evaluations
1. To approve documents for adequacy prior to use		GS, GM		This documented procedure shall be developed
2. To review and update as necessary and re-approve documents		GS, GM		This documented procedure shall be developed
3. To ensure that changes and the current revision status of the documents are identified		GS, GM		This documented procedure shall be developed
4. To ensure that relevant versions of applicable documents are available at point of use		GS, GM		This documented procedure shall be developed

5. To ensure that documents remain legible and readily identifiable		GS, GM		This documented procedure shall be developed
6. To ensure that documents of external origin determined by the organization to be necessary for the planning, operation of the QMS are identified and their distribution controlled		GS, GM		This documented procedure shall be developed
7. To prevent the unintended use of obsolete documents, and to apply suitable identification to them if they are retained for any purpose		GS, GM		This documented procedure shall be developed

Table 96 Gap evaluation: ISOR 10 – Documentation requirements for QMS - control of records

ISO 9001:2008 sub-requirements	ADP's processes	ADP's stakeholders	ADP's supporting documents	Gap evaluations
1. A documented procedure to define the control needed for the identification, storage, protection, retrieval, retention and disposition of records		GS, GM		This documented procedure shall be developed

Appendix E: Case study 2 - Integrating learning through design methodologies in aircraft design

E.1 Introduction

The purpose of this appendix is to document additional content to the case study in Chapter 6. In particular, the appendix documents additional content related to general facts about aircrafts (Section E.2), alternative life cycle model in aircraft design (Section E.3), Canadian aerospace supply chain (Section E.4), and quantities, units, measurement & inspection methods, and taxonomy of attributes in aircraft design (Section E.5).

E.2 General facts about aircrafts

This section introduces general facts about aircrafts. The facts are summarized in figures. Fig. 167 depicts the routes where aircrafts fly globally. Fig. 168 lists manufacturers and models of new civil airplanes expected to enter to service until 2030. Fig. 169 defines selected civil airplane models, number built/ordered as of 2012, development time in years, year entered service, development costs, development costs/seats, and development cost/seat built. Sometimes, aircraft manufacturers are classified depending on the number of seats their civil airplanes have; as shown in Fig. 170. Fig. 171 defines civil airplanes delivery since 1950 respect to aircraft models, variants, and aircraft manufacturers. Fig. 172 defines maturation timeline for TRL (technology readiness level) for principle aircraft technologies (i.e., airframe, engine, and flight controls). Finally, Fig. 173 describes the evolution of requirements over time with special attention to design range, number of seats and payload.

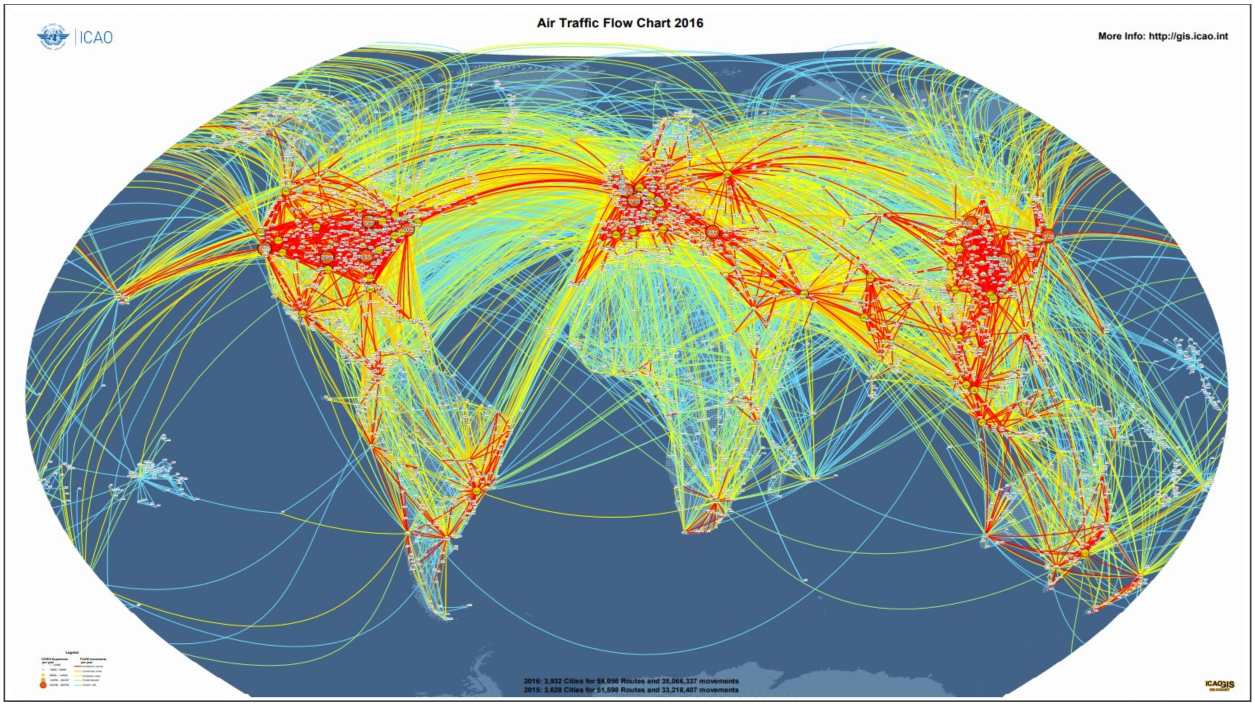


Fig. 167 Air traffic flow chart 2016 (ICAO, 2016)

	Year	Manufacturer	Model	Variant
2010 - 2020	2014	Airbus	A350	A350-900
	2014	Bombardier	C-Series	CS-100
	2014	Comac/ACAC	ARJ21	
	2015	Bombardier	C-Series	CS-300
	2016	Airbus	A350	A350-800
	2016	Airbus	A320neo	
	2016	Comac	C919	
	2017	Airbus	A350	A350-1000
	2017	Boeing	A737max	
	2017	Mitsubishi	MRJ	
	2019	Boeing	B777-8	
2020 - 2030	2025	Airbus	A30X	NSR
	2025	Boeing	Y1	NSR
	2030	Boeing	B777 Successor	NLR
	2030	Airbus	A330 Successor	NLR

Fig. 168 Entry into service timeline for future aircrafts (IATA et al., 2013, p. 50)

Aircraft Model	Number built/ ordered as of 2012	Development Time in Years	Year Entered Service	Development Costs	Development Costs/Seats	Development Cost/Seat Built
					(in constant 2012 US$)	
DC-3	607	2	1936	4.8M	0.23M	3770
DC-6	704	3	1947	161M	2.88M	4084
B707	1010	6	1958	1453M	10.38M	10,276
B747	521	4	1970	5500M	12.17M	23,355
DC-8	556	7	1959	1011M	12.64M	227,299
B777	400	6	1995	7800M	19.50M	14,265
A380	253	7	2007	16,100M	30.67M	121,212
A350	555	7	2013	15,200M	55.07M	99,229
Concorde	20	9	1976	11,495M	114.95M	5,750,000
B787	873	7	2011	32,000M	121.21M	138,845

Fig. 169 Development costs of selected past and current aircraft programs – new designs (IATA et al., 2013, p. 63)

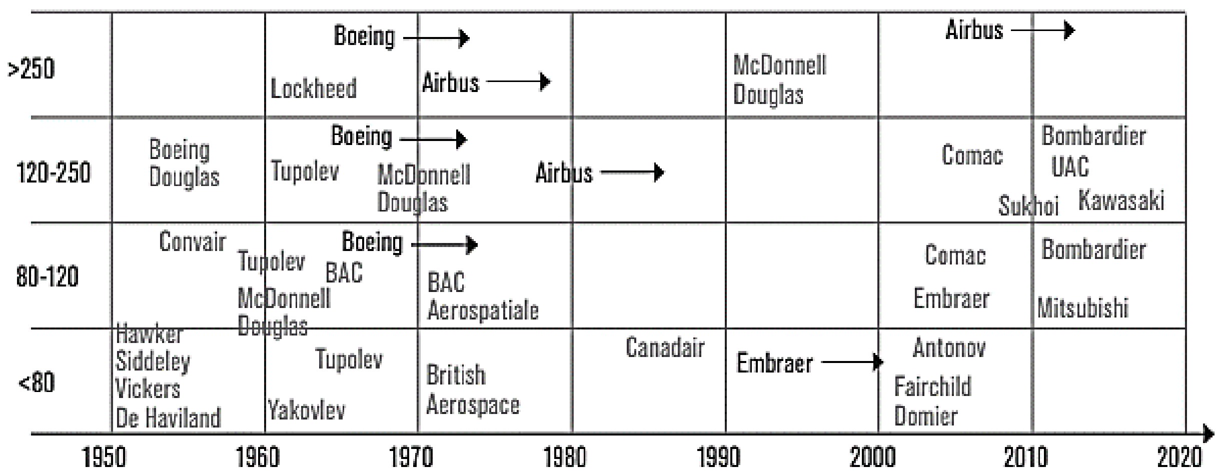


Fig. 170 Aircraft manufacturers launching programs in different seat categories over time (IATA et al., 2013, p. 66)

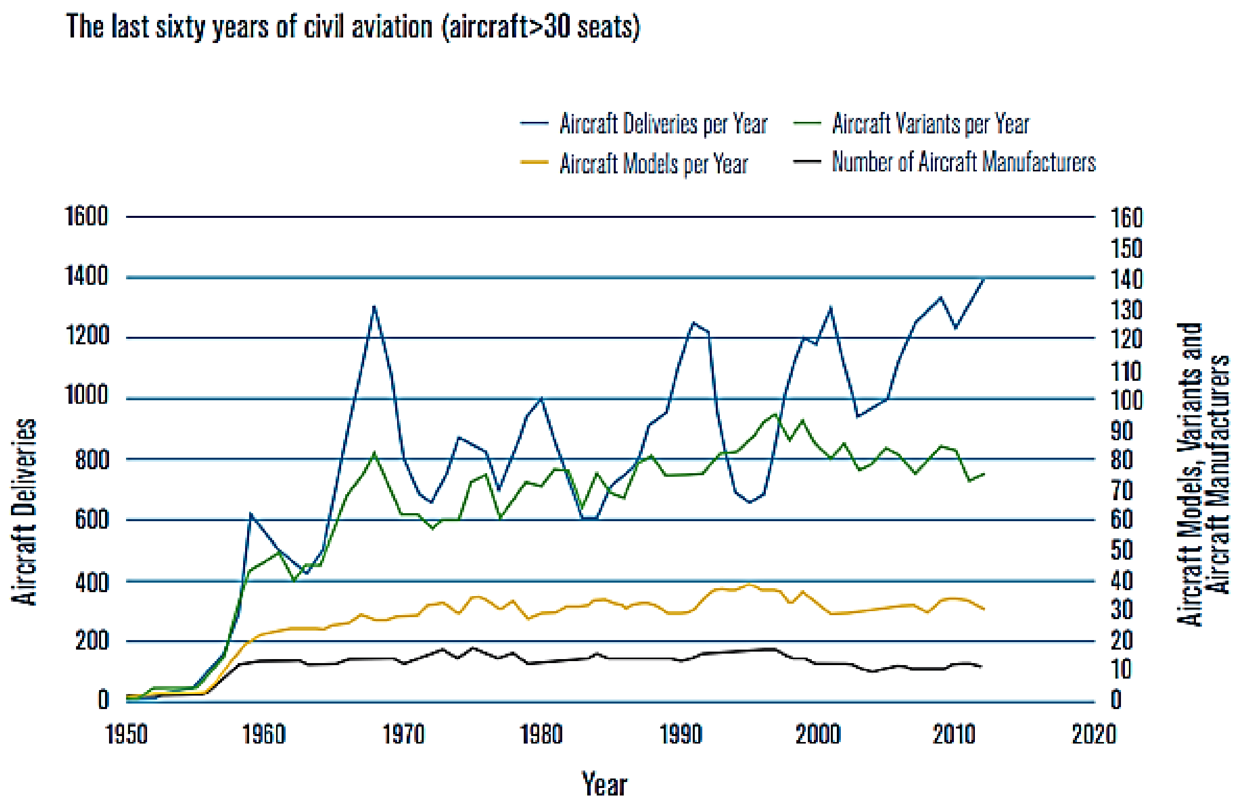


Fig. 171 Civil aircraft delivery: number of models, variants, and manufacturers including only turboprop, jet, and turbofan propelled aircraft (piston engines excluded) (IATA et al., 2013, p. 67)

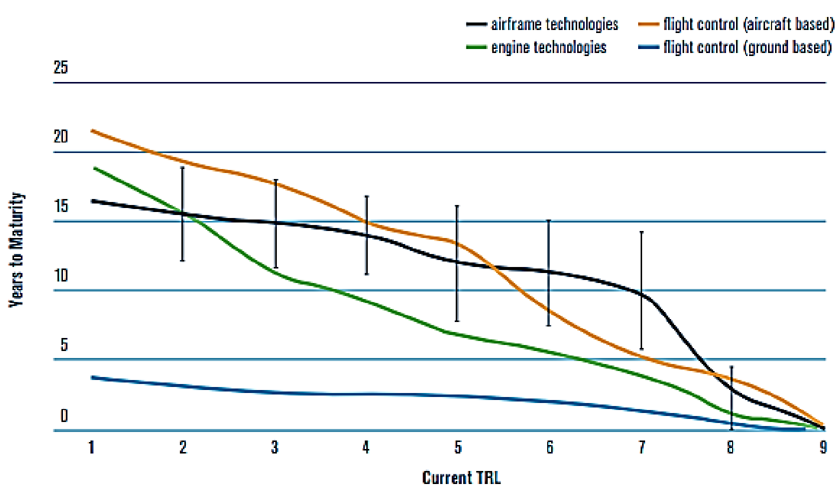


Fig. 172 Maturation timeline for TRL (IATA et al., 2013, p. 61)

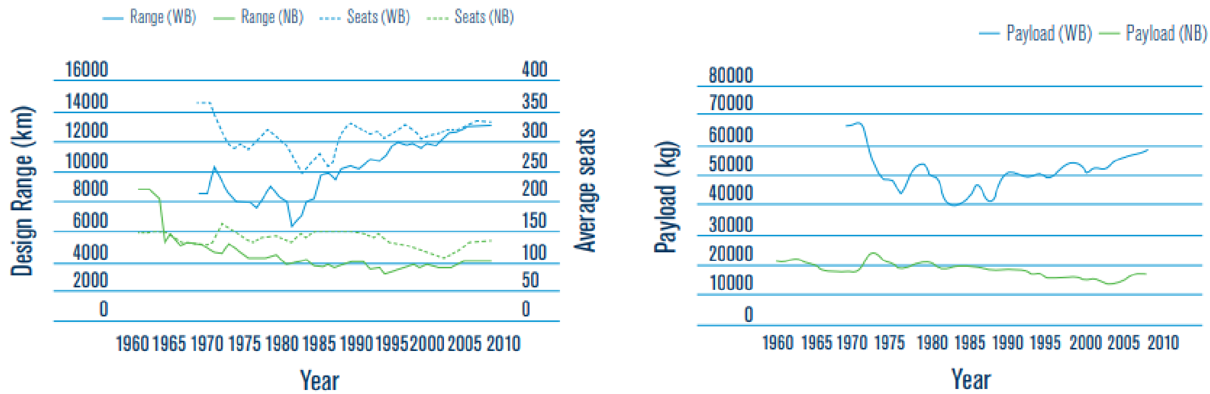


Fig. 173 The evolution of requirements over time: design range, and number of seats (left); maximum payload (right) (IATA et al., 2013, p. 67)

E.3 Alternative life cycle models in aircraft design

Life cycle models in aircraft design were introduced in Chapter 6. There are alternative life cycle models to the ones introduced in Chapter 6. Alternative life cycle models identified while working in Chapter 6 are presented in this section using figures. Fig. 174 describes a life cycle model titled Bombardier aerospace engineering system. Fig. 175 describes a life cycle model titled aviation industry activities relevant to aircraft life cycle.

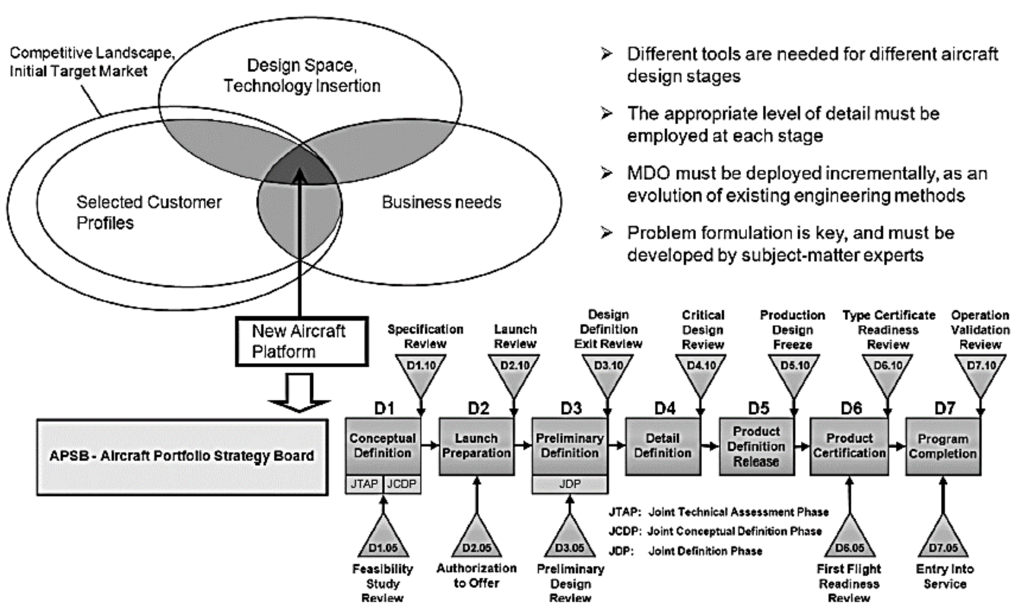


Fig. 174 Bombardier aerospace engineering system (Piperni et al., 2013)

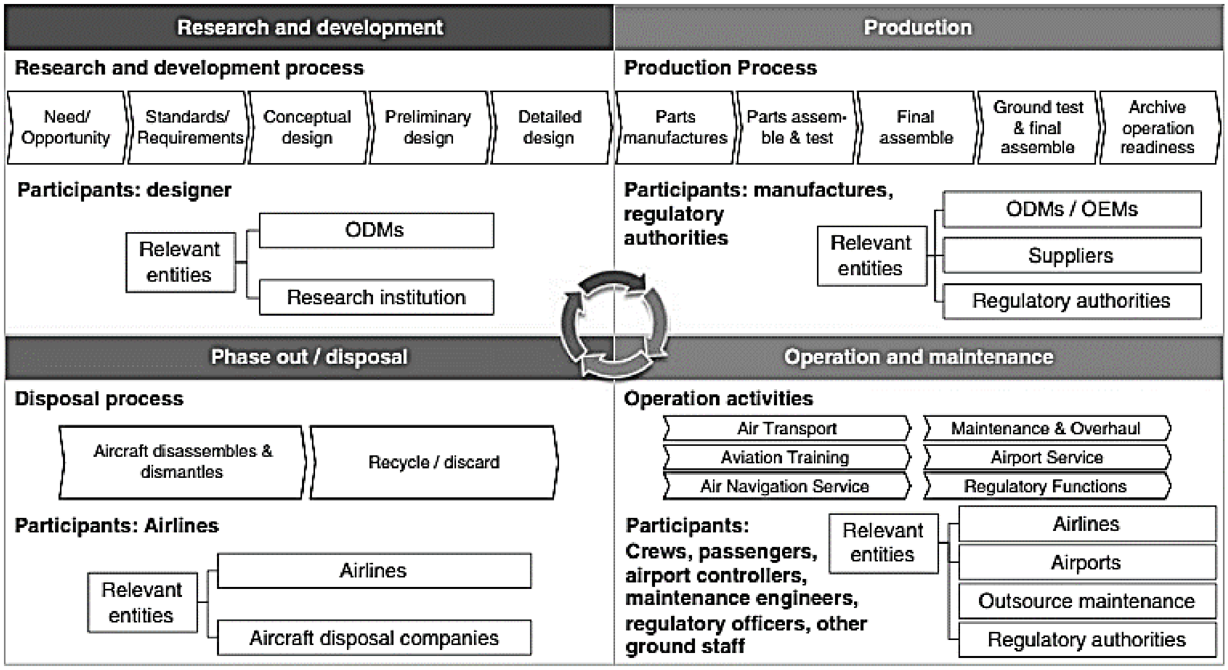


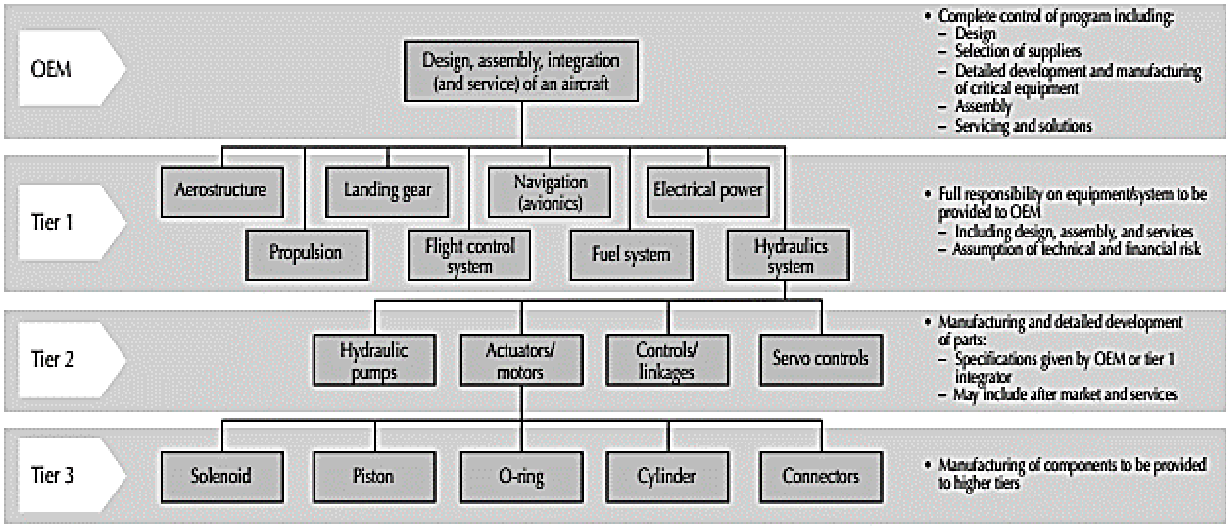
Fig. 175 Aviation industry activities relevant to aircraft life cycle (Richard Curran et al., 2015)

E.4 Canadian aerospace supply chain

The Canadian aerospace supply chain is organized into clusters. The clusters are located in different provinces in the country. Table 97 defines the aerospace clusters in Canada. The table defines the components and leading companies in the clusters. In general, the components and leading companies shall be allocated to a taxonomy of aircraft systems. For example, Fig. 176 defines a tier structure of the Canadian aerospace industry for the production of an aircraft. Considering such tiers, Table 98 intents to allocate the components and leading companies.

Table 97 Aerospace clusters in Canada (Global Affairs Canada, 2016)

Cluster	Components	Leading companies
Western provinces	Aerostructures, composites, airframe MRO, helicopter MRO, defence electronics, space systems, earth observation, engines, engine MRO, small-aircraft manufacturing, cold-weather engine testing	Asco Aerospace Canada Ltd., Avcorp, Boeing Canada, Cascade Aerospace (IMP Group), Vector Aerospace (Airbus Group), General Dynamics Canada, KF Aerospace, Magellan Aerospace, MacDonald Dettwiler and Associates (MDA), Pratt and Whitney Canada (P&WC), StandardAero, Viking Air Ltd
Ontario	Rotorcraft manufacturer, commercial and business aircraft, satellite-payload subsystems, landing gear, ECS, electrical power, engine parts, MRO space robotics, display systems, aerostructures, gears and gears assemblies, engines	Airbus Helicopters Canada, Bombardier, United Technologies Aerospace Systems, Honeywell Canada, Magellan Aerospace, MDA, Messier-Bugatti-Dowty, L-3 Electronic Systems Services, MHI Canada Aerospace, Northstar Aerospace, P&WC
Quebec	Aerostructures, civil helicopters, commercial and business aircraft, training and simulation, avionics, engine components, landing gear, engines, engine MRO	Aerolia, Bell Helicopter, Bombardier, CAE, Esterline CMC Electronics, GE Canada, Heroux-Devtek, LISI, Mechtronix, P&WC, Premier aviation, Rolls-Royce Canada, Safran, Stelia, Thales Canada, Turbomeca Canada
Atlantic Provinces	Precision machining and complex assemblies, composites, gas turbine MRO, MRO, design and manufacturing, engines	APEX industries, Bluedrop, Vector Aerospace (Airbus Group), IMP Group, P&WC, Slemon Park



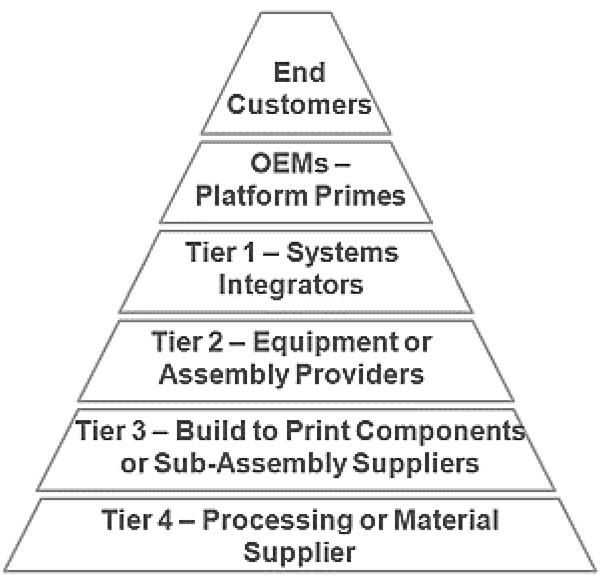
Source: Adapted from PricewaterhouseCoopers, *Globalisation in Aerospace and Defence*, January 30, 2008.

For more information regarding the aerospace industry's tier structure and examples of Canadian companies within each tier, please refer to the *Final Report of the Supply Chain Working Group*, "Structure of Aerospace Industry in Canada."

OEM = original equipment manufacturer

Fig. 176 Tier structure of the Canadian aerospace industry for the production of an aircraft (Emerson, 2012, p. 13)

Table 98 Structure of the aerospace industry in Canada (Supply Chain Development Working Group, 2012, pp. 9-10)

	***Trend:*** due to global competition, OEM airframe manufacturers (e.g., Boeing, Airbus and Bombardier) are forced to move from a business model with many direct supplier relationships to one where they partner with fewer Tier 1 systems integrators meaning awarding more business in greater scope to larger integrators. Tier 1 systems integrator are following the same approach. This ultimate leads to the concentration of aerospace work globally with fewer large Tier 1 and 2 firms. The ultimate goal of OEM is to 1) meet lower operating costs and more efficient aircraft, 2) maintain a viable competitive offering to end customers, and 3) reduce risk (e.g., financial burden) and

	complexity. Refer also to (Emerson, 2012, p. 26).
- End customers: entities buying the aircraft such as airlines, defense, and other organizations. They drive needs such as need for competitiveness, improved technology and reduced operating costs. - OEM: companies assembling, marketing and selling the final aircraft platform to end customers. Canadian examples are Bombardier and Bell Helicopters. - Tier 1: companies engaged in the integrated design, development, manufacture and marketing of major aircraft systems such as landing gear systems, environmental control systems, navigation systems, communication systems, avionics systems and propulsion systems. Also, companies designing and manufacturing complete large, complex structures such as fuselage systems, empennage (tail) assemblies or wings. Examples of Canadian companies are: Pratt and Whitney Canada, GE Canada, Rolls Royce Canada, etc. - Tier 2: companies engaged in designing, developing, manufacturing, and marketing of engineered and proprietary equipment and sub-systems such as sensors, instruments, actuators, displays, communications equipment, aerostructure, etc.; typically having their company name on the products' drawings. Tier 2 suppliers may also be subcontractors delivering complex products with many components obtained from their own manufacturing operations and from a variety of outside suppliers. Customers of tier 2 suppliers are typically tier 1 or OEM firms, for example in Canada, Sonaca Montreal, Aerolia, etc. - Tier 3: firms are parts or assembly suppliers acting as subcontractors that manufacture or supply components and sub-assemblies such as machined components, minor assemblies. Customers are typically tier 1 and 2, and often other tier 3; being OEMs less common. Examples in Canada are RTI Claro, Noranco, Celestica, etc. - Tier 4: firms providing processing services for components (e.g., shot peening, heat treatment, plating, coating, etc.) and companies providing raw materials (e.g., aluminum, steel, titanium, composites, etc. Also, companies supplying standard components such as hardware and wiring or harnesses. Customers are typically tier 2 and 3 firms. Examples in Canada are Interfast, Vac Aero, and Aero Tek.	

E.5 Quantities, units, measurement & inspection methods, and taxonomy of attributes in aircraft design

Aircrafts are safe man-made devices. To achieve safety, several aspects play an important role: quantities, units, measurement & inspection methods, and attributes. Fig. 177 depicts the 14 categories of sources of quantity defined by ISO/IEC 80000. Each category is related to a specific international standard. The SI quantities and units defined in Fig. 178 conform the core to characterize the quantities in Fig. 177. Fig. 179 defines a taxonomy of attributes that are of interest in product design, but it needs to be associated to SI quantities and units. Finally, Fig. 180 categorizes measurement and inspection methods needed to quantify SI quantities and units.

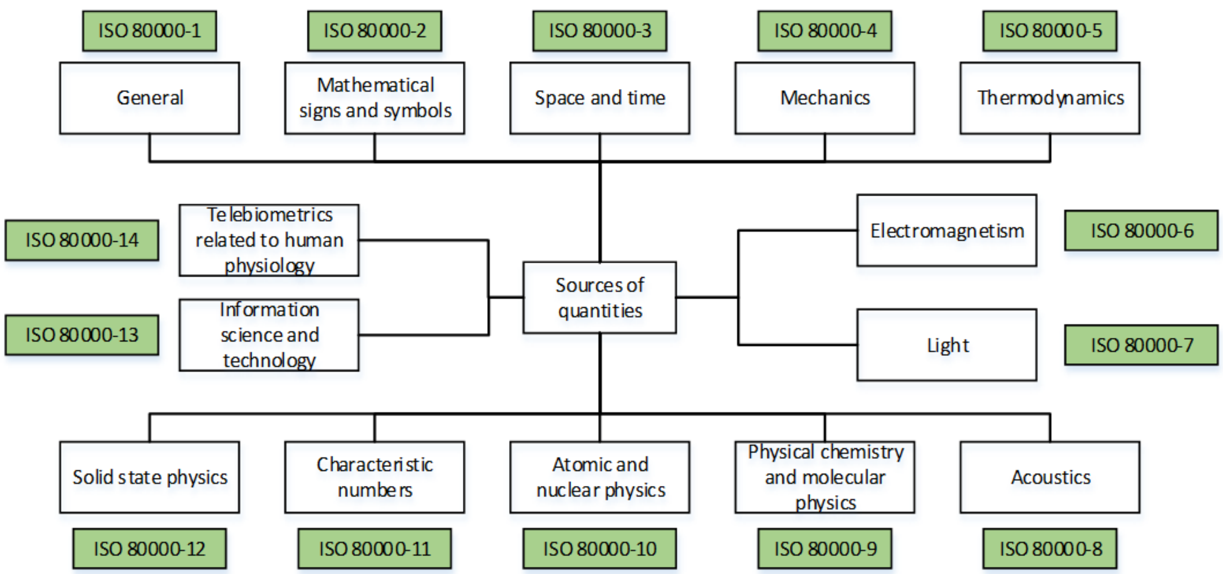


Fig. 177 Quantity and units in ISO/IEC 80000

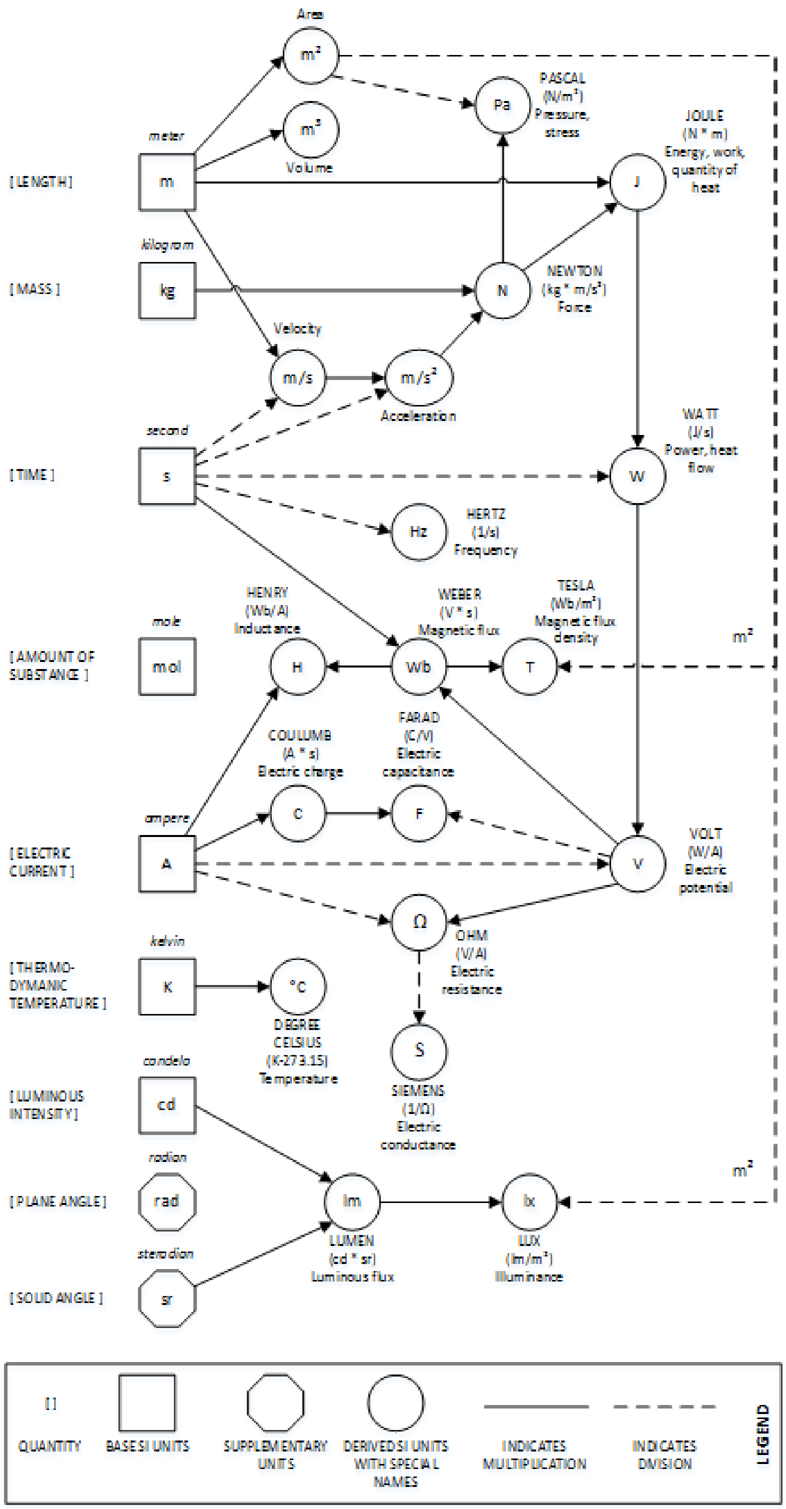


Fig. 178 Quantities, International System (SI) units (base, supplementary and derived) with special names – adapted from Black and Kohser (2008, p. 215), NIST (2008, p. 78), and Williams (2017)

- Auditory
  - Loudness
  - Pitch
  - Timbre
- Environmental
  - Barometric pressure
  - Dirt/Dust
  - Humidity
  - Particulate Concentration
  - Precipitation
  - Temperature
  - Visibility
  - Wind speed
  - Wind direction
- Financial
  - Cost
  - Price
- Geometric
  - Area
  - Configuration
  - Dimension
  - Direction
  - Location
  - Perimeter
  - Shape
  - Volume
- Identification
  - Appearance
  - Classification (e.g., species)
  - Instantiation (e.g., serial number)
  - Logo
  - Motto
  - Name
- Quality Rating
- Mechanics
  - Angular momentum
  - Force
  - Kinetic Energy
  - Intensity
  - Mass
  - Momentum
  - Potential Energy
  - Power
  - Pressure
  - Torque
  - Work
- Motion
  - Acceleration
  - Angular Acceleration
  - Angular Velocity
  - Deformation
  - Displacement
  - Motion
  - Rotation
  - Translation
  - Velocity
  - Vibration
- Quantity
- Material
  - Acoustic
    - Acoustic Absorption
    - Refractive Index
  - Chemical
    - Activation Energy
    - Biodegradation
    - Chemical Energy
    - Concentration
    - Electro-negativity
    - Half-life
    - Hydrophobicity
    - Hygroscopy
    - Ionization Potential
    - Odor
    - pH
    - Radioactivity
    - Reactivity
    - Solubility
    - Surface Energy
    - Surface Tension
    - Taste
    - Toxicity
  - Electrical
    - Arc Resistance
    - Capacitance
    - Charge
    - Current
    - Comparative Tracking Index
    - Conductivity
    - Dielectric Constant
    - Dielectric Strength
    - Dissipation Factor
    - Electromagnetic energy
    - Inductance
    - Magnetic flux density
    - Permittivity
    - Potential difference
    - Power
    - Resistance
    - Surface Resistance
  - Failure
    - Buckling
    - Corrosion
    - Creep
    - Fatigue
    - Fracture
    - Impact
    - Mechanical Overload
    - Melting
    - Thermal Shock
    - Wear
    - Yielding
  - Fluidic
    - Reynolds Number
    - Viscosity
  - Mechanical
    - Compressibility
    - Elongation
      - Elongation at Yield
      - Elongation at Break
    - Friction coefficient
    - Machineability Rating
    - Modulus
      - Compressive Modulus of Elasticity
      - Modulus of Rigidity
      - Modulus of Toughness
      - Secant Modulus
      - Shear Modulus
      - Specific Modulus
      - Tensile Modulus
    - Moment of Inertia
    - Piezoelectric Constant
    - Poissons Ratio
    - Strength
      - Charpy Impact
      - Compressive Yield Strength
      - Ductility
      - Fatigue Strength
      - Fracture Toughness
      - Hardness
      - Izod Impact
      - Malleability
      - Rupture Strength
      - Tensile Strength at Yield
      - Tensile Strength at Break
  - Optical
    - Absorptivity
    - Emissivity
    - Color
    - Gloss
    - Haze
    - Luminosity
    - Photosensitivity
    - Reflection Coefficient
    - Refractive Index
    - Transmittance
    - Visible Transmission
  - Physical
    - Material Type
    - Composition
    - Density
    - Linear Mold Shrinkage
    - Melt Flow Index
    - Moisture Vapor Transmission
    - Oxygen Transmission
    - Porosity
    - Surface Roughness
    - Water Absorption
      - Moisture Absorption at Equilibrium
      - Water Absorption
      - Water Absorption at Saturation
  - Thermal
    - Coefficient of Thermal Expansion
    - Emissivity
    - Enthalpy
    - Entropy
    - Flammability
    - Heat of Combustion
    - Material Phase
    - Oxygen Index
    - Phase Transition
      - Autoignition Temperature
      - Boiling Point
      - Critical Temperature
      - Curie Point
      - Deflection Temperature
      - Eutetic Point
      - Fire Point
      - Flash Point
      - Freezing Point
      - Glass Transition Temperature
      - Heat Distortion Temperature
      - Heat of Fusion
      - Heat of Sublimation
      - Heat of Vaporization
      - Liquidus Temperature
      - Melting Point
      - Softening Point
      - Solidus Temperature
      - Triple Point
    - Pyrophoricity
    - Seebeck Coefficient
    - Service Temperature
      - Hot Ball Pressure Test
      - Maximum Service Temperature
      - UL RTI
    - Specific Heat Capacity
    - Temperature
    - Thermal Conductivity
    - Thermal Diffusivity
    - Thermal Energy
    - Vapor Pressure
- Signal
  - Amplitude
  - Attenuation
  - Frequency
  - Phase
  - Wavelength
- Time
  - Duration
  - Frequency

Fig. 179 Taxonomy of attributes (Weissman, Gupta, Fiorentini, Rachuri, & Sriram, 2009, pp. ii - Appendix B)

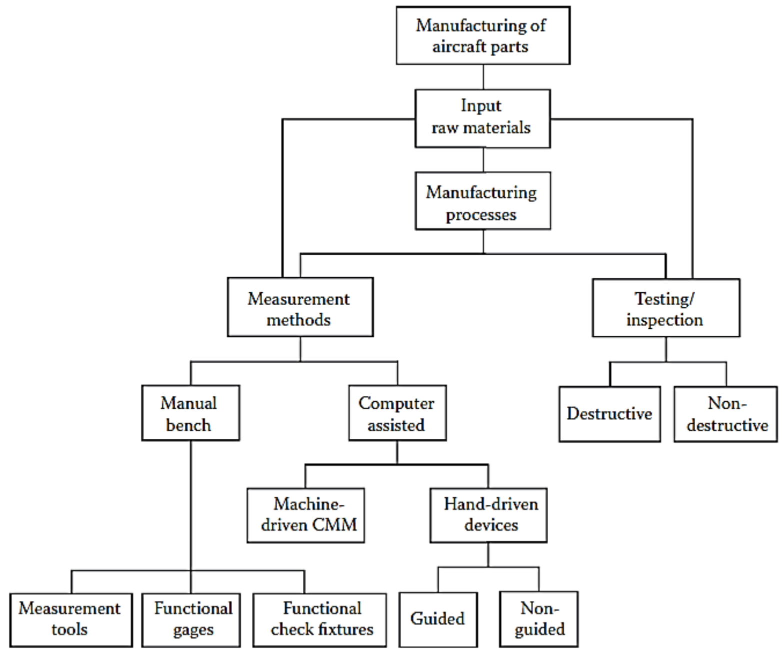


Fig. 180 Measurement and inspection methods (Saha, 2017, p. 436)