A parallelistic approach toward ontology design to overcome system's nuance in decision governance

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Abstract: Artificial intelligence (AI) or machine intelligence (MI) can be faster and more accurate in domain specific decision tasks than human, however, AI's inability to achieve true general human creative cognitive capacity is still a deficiency in the AI or MI decision-making systems. The fundamental problem of decision-making governance, thus, poses a great challenge in advancing human-intelligent and machine-intelligent systems. The purpose of this paper is to present a noble parallelistic approach that has recently been applied to build a top-level ontology for HI-MI decision governance. The objective of this paper thus is threefold: 1) to address the gap in existing knowledge in decision governance for HI-MI systems and as a potential solution to the problem; 2) outline an integrative methodology to detailing the top to application level ontological development, resulting in; 3) a more specific 'parallelistic approach' for the development of a top ontology for human-machine intelligence decision governance.

Keywords: systems engineering; knowledge generation; ontology; system's nuance; decision governance; parallelistic approach.

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1 Introduction

The historical background of human-machine intelligence (HMI) reveals four distinctive areas such as human to human intelligence, human to machine intelligence, machine to machine intelligence and machine to human intelligence. Regardless of the ongoing research and major development within and surrounding human and machine intelligence, mostly in the application level, there has been little to no work in either transferring knowledge gained in machine to human applications or in the decision interactions between cognitively intelligent humans and artificially intelligent machines. At the same time, there has been little to no research conducted toward establishment of governance ontologies in other disciplines. All the existing work in developing human-machine systems thus, are based on best practices and/or standards that differ from organisation to organisation and from government to government without having a universal knowledge-base as well as a common ground for the same concept and knowledge sharing.

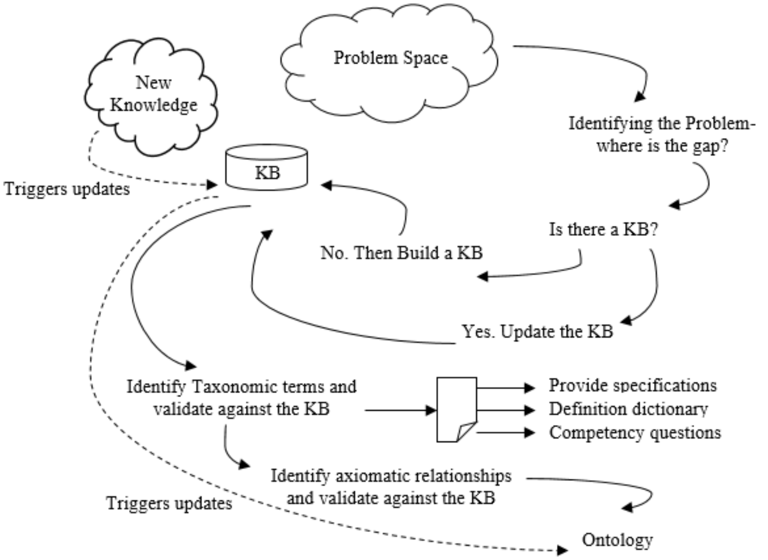
Given that knowledge is already attained and out there, ontology and its framework make that knowledge clearer, precise and structured to aim for the right target. Precisely speaking, ontological framework clarifies the structure of knowledge. The use of ontology is neither limited to any particular field/domain nor have restrictions or constraints of using it. When knowledge needs to be furthered to gain more insights, ontological analysis becomes a better option.

Tracing back to its philosophical origin, 'ontology' is derived from two Greek words – 'ontos' meaning being and 'logos' meaning logical argument or discourse or debate. Thus, ontology means to understand the beingness or existence of anything by providing supportive evidence. Concisely, ontology provides the foundation necessary to understand the theory of existence of a thing or concept. To answer the question 'what' with rooted explanations in any domain of discourse reveals this concept. Many definitions of ontology have been set forth by different researchers, scientists, engineers and practitioners. In the artificial intelligence (AI) community, the widely received, accepted and cited definition was given by Gruber (1993).

According to Gruber, ontology is an explicit representation of a conceptualisation. Even though, this definition was given from a local or application level within ontology classification, it captures the basic idea of ontology. While building or developing ontology, it is therefore, not just to give the definition of a concept, but, also to identify the classes or categories associated with and within that concept, find the relationships within and among those classes or categories, as well as their functions, axioms and instances, depending on the type or level of the ontology. Ontology allows us to capture as much information as possible about a concept or domain of discourse to bridge the gap of any existing knowledge as well as to generate new knowledge to expend it in the application level.

In absence of an expert reference-base or knowledge-base, the first thing to accomplish is to establish the platform itself. Figure 1 (Mahmud and Zahedi, 2018) shows relationships of different queries to exploit an ontology. As ontology is not static in nature, rather dynamic, it requires updates and refinements with the addition of new knowledge. Thus, both knowledge-base and ontology act in sequence where the former triggers the revision of the latter.

Figure 1 Knowledge-base and ontology



2 Related work

Despite the revolution of digital and technology in the applications level, there has been little to no research in addressing the question of decision-making governance in Human-intelligence and machine-intelligence (HI-MI) systems. There also exist no foundational, core reference or domain ontologies for HI-MI decision governance systems. In parallel, search of the governance literature produced only few corporate, information technology and knowledge governance taxonomies. Whether it is a corporate governance taxonomy (Weimer and Pape, 1999), furthered by a composite taxonomy (Keenan and Aggestam, 2001), or a governance typology (Stout and Love, 2015), there appears no other viable discussions on how to incorporate human and machine intelligence within a decision governance framework. Within the systems level, there are substantial discussions on integrated systems (Gheorghe et al., 2018), complex system governance challenges (Keating et al., 2014) and emergent behaviour in complex systems engineering (Mittal et al., 2018) emphasising on predicting system's behaviour and challenges, articulation of governance and subsequently, providing a paradigm for complex system governance, respectively. Nevertheless, these discussions did not dissect another dimension to incorporate level-by-level systematic development of ontologies to offer new knowledge and insights for potential candidate of overcoming system's nuance in decision governance. Conversely, organisations and corporate industries are having their own standards and protocols to design, build and implement AI enabled machines to assist human counterparts. However, in absence of a universal expert reference-base or body of knowledge (BoK) integrated with an ontological framework, decision makers must rely on best practices or standards that differ from organisation to organisation and from government to government, contributing to systems failure in complex mission critical situations. It is still debatable whether and when human or machine decision capacity should govern or when a joint HI-MI decision capacity is required in any given decision situation.

Ontology, as a formal representation of domain-specific knowledge, can be used to address this problem, through solving the semantic ambiguities between the two parties (Dong et al., 2011). And by 'two parties', it means humans and machines. The definition of ontology given by Gruber (1993) identifies three keywords – explicitness, specification and conceptualisation. Thus, ontology is not just to define a domain of discourse with a formal definition, rather going further to identify the terms/classes/categories for that domain of discourse, meaning what terms directly or indirectly constitute the domain. Then, finding their (terms) relationships, functions, axioms and instances depending on the level or type of ontology one is developing.

Noy and McGuinness (2001) outlined ontology, "in reality, there is a fine line where the ontology ends, and the knowledge base begins." This definition brings some theoretical requirements for ontology such as to elaborate the taxonomic terms or classes of a concept, their relationships, functions and axiomatic relationships to cover the depth and breadth of the knowledge-base. Further, ontological analysis clarifies the structure of knowledge. Given a domain, ontology forms the heart of any system of knowledge representation for that domain (Chandrasekaran et al., 1999).

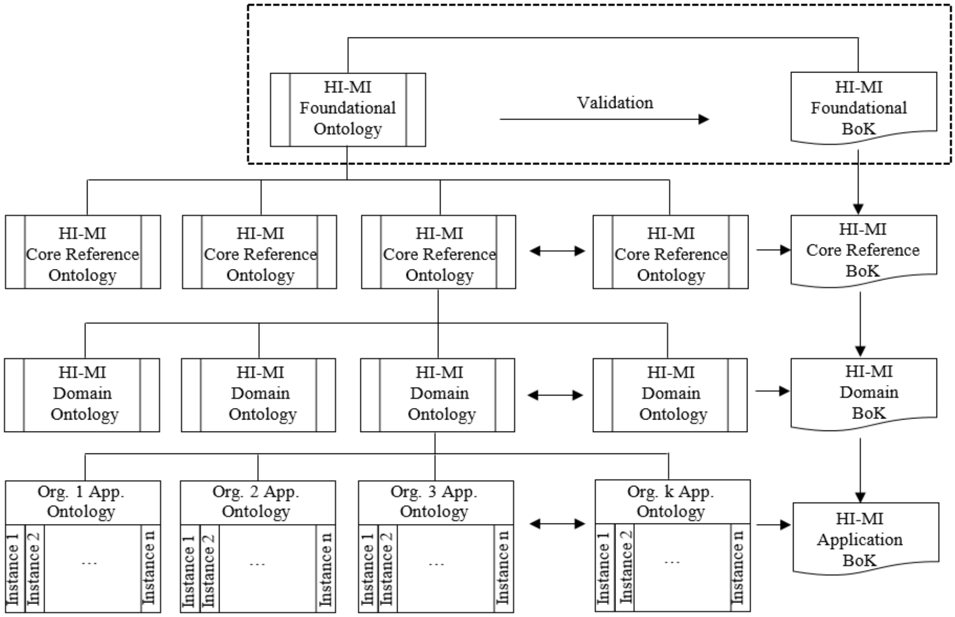
For the sake of the paper length, this article will neither cover the details of various levels of ontology nor the foundational ontology being developed for HI-MI decision governance. However, the methodologies discussed here are the primary focus of the paper and are already applied for the development of a formal top/foundational ontology, specifically into the ontological aspect of human-machine decision governance from a system's perspective. Therefore, the principal focus is not to explain the ontology that is being developed, rather the overall methodology used to build the ontology. First an integrative methodology is discussed to clarify how the different levels of ontologies can be built incorporating various domains of influence by going to their seminal work. Then, a more specific one, the 'parallelistic approach' is explained with supportive evidences.

3 Methodology

3.1 Data collection

The data used and analysed for this inquiry are qualitative in nature and text-based that are comprised of peer reviewed articles, journal papers, seminal books and book chapters. Restricted governmental or classified articles are not considered as those are not accessible. Traditional ontology development methodology is built relying on existing knowledge-base extracted from either interviewing experts or/and synthesising meta-knowledge from the seminal work of the tangential domains by reviewing and integrating literature corpus (Uschold and King, 1995; Gómez-Pérez, 1999). Thus, top/foundational ontology must form the taxonomic and axiomatic foundation for a given knowledge-base. However, there does not exist an expert panel or body at the HI-MI decision governance foundational knowledge level theoretical population where interview-based knowledge extraction can be considered. The only viable way to create a knowledge-base is to first identify the accessible population of seminal and supporting literature in the identified knowledge domains and then, synthesise that into a foundational ontology and BoK.

Figure 2 General integrative approach to HI-MI decision governance theory and BoK



3.2 *The integrative knowledge generation ontological engineering methodology*

The integrative approach (Figure 2) toward developing the general HI-MI decision governance theory and BoK was first proposed by Cotter (2015) and then, modified (Mahmud and Cotter, 2017) later to capture the overall picture in developing different levels of ontology with corresponding cross-validation against a theoretical BoK. The general research approach shown here is a top-down approach which means that the very first ontology to build is the foundational or top ontology, then core-reference, domain and application or local ontologies.

The advantage of having a top-down approach over bottom-up is that:

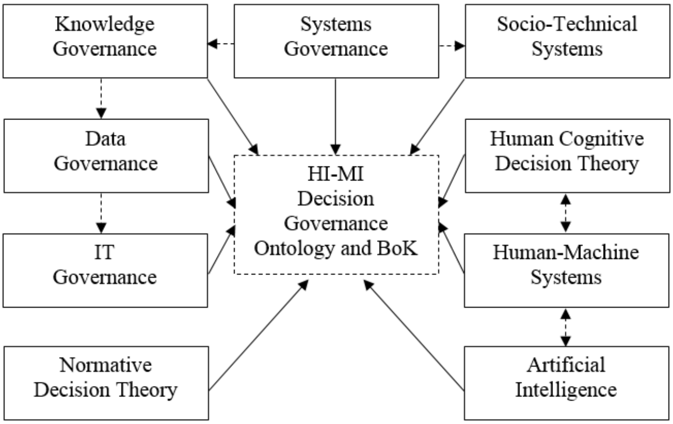
1 it has more control on the overall modelling of a particular domain of discourse

2 it can be aligned with sub-sequent levels of ontological development properly

3 it can be extended with other domain of discourse for knowledge generation and sharing.

Further, a top-down approach ensures interoperability criteria. The area inside the dotted lines (Figure 2) is for the top or foundational level ontology for HI-MI decision governance. The validation here takes place against the HI-MI foundational BoK. As we go down, there are core-reference ontology, domain ontology and all the way to the bottom is the application or local level ontologies. Each of these ontological developments must be validated against the identified and gathered BoK for that particular level.

Figure 3 The domains of influence for HI-MI decision governance BoK and ontology



The foundational ontology for HI-MI decision governance proposes the integration of existing socio-technical systems knowledge with decision theory and AI declarative and procedural knowledge into a human-intelligence and machine-intelligence systems theoretical framework and BoK (Figure 3). These areas, therefore, known as the ‘domains of influence’ for developing HI-MI decision governance BoK and ontology.

3.3 Parallelistic approach

The knowledge generation approach to ontological engineering integrates the development of a BoK and its supporting ontology. The methodology begins by assembling a corpus of peer reviewed works traced to their supporting seminal knowledge about the phenomenon of interest. Now, the general methodology re-directs to a more specific approach for ontology and BoK development, i.e., how to build the BoK and foundational ontology and what phases, validations, etc. must take place in the process of developing such knowledge-base.

Since new or extended knowledge is not considered valid until it has passed a peer review process(s) and been published, this methodology on knowledge generation ontological engineering process is based on gathering and jointly modelling a given body of peer reviewed works traced to their supporting seminal knowledge while simultaneously engineering the supporting ontology. The notion of including an expert panel and interview-based data collection is not worthy here, as there appears not having such an expert panel that we can interview. Expert panel interviews thus, only seem reasonable in the application level or may be in the domain level ontology development. Thus, the only other way to gather knowledge is by relying on existing peer reviewed articles, journals, synthesised books and book chapters. The knowledge generation approach to ontological engineering thus, integrates:

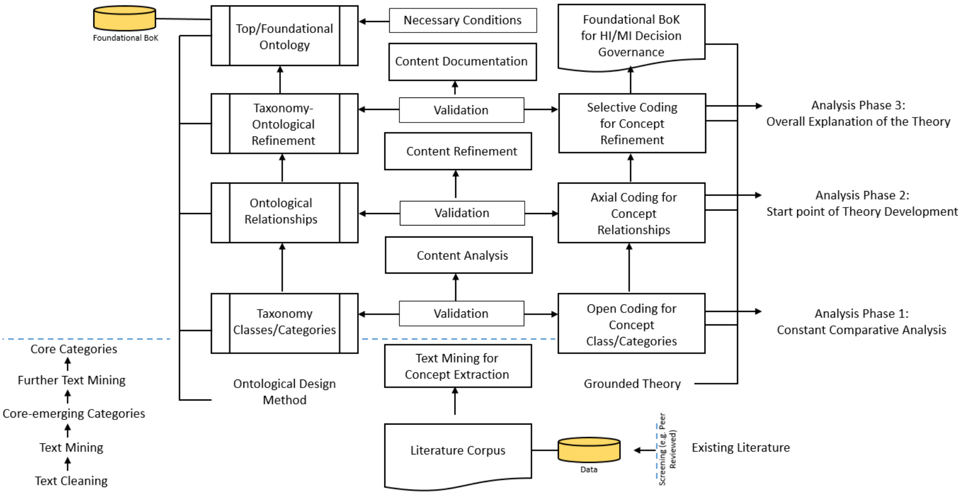
1 the theoretical construction and development of grounded theory and synthesising meta-knowledge as the foundation for building the validated BoK

2 the appropriate ontological design method for the target ontology's level and type

3 text mining and content analysis to support concept extraction and concept relationships extraction for BoK development and ontology engineering.

The knowledge generation approach to ontological engineering seeks to mitigate the incomplete knowledge emergence limitation by integrating and validating theory and ontology development against each other.

Figure 4 Parallelistic approach to HI-MI decision governance theory and BoK (see online version for colours)



The specific parallelistic approach (Figure 4) further explores various phases for BoK and ontology development.

Initially, the corpus is categorised based on research focus by applying the grounded theory open coding process. The corpus is judged to reach saturation when the identified conceptual categories span and describe the dimensions of the BoK of the phenomenon of interest and the literature within each category achieves redundancy (i.e., reaches diminishing returns in that the inclusion of additional works provide no new or only minor information) (Bowen, 2008).

Next, text mining and content analysis are applied as exploratory tools to extract manifest and latent concepts. Text mining provides lexical information on key term clusters and their distributions. Separation between clusters indicates their exclusiveness as a manifest or latent category and the distributional properties indicate coverage of the BoK.

Content analysis is applied to analyse information patterns within clusters. The structure of the patterns within categories suggests manifest and latent subcategories and how completely they specify knowledge within the category. Identified categories and subcategories are applied as the initial codes for grounded theory open coding and tested to determine the degree to which they describe knowledge concepts, theories and principles of the phenomenon. Resultant category and subcategory codes are adjusted and become the taxonomic seed categories and subcategories for the ontology and the core concepts categories and subcategories for the BoK. Content analysis is applied to examine concept relationship patterns among subcategories within categories and among categories. These concept relationship patterns are applied as the initial relationships for grounded theory axial coding, or research synthesis models and tested for fit to the relationships among knowledge concepts, theories and principles of the phenomenon.

Concept categories, subcategories, and relationships are refined through selective coding based on fit to concepts, theories and principles and become the axioms and functions for the ontology and BoK. The ontology, finally, is published for review and refinement before being released for use.

It is the identification of latent categories and subcategories and the synthesis of relationships among and within them that admits knowledge generation in this methodology. In the historical knowledge representation methods of ontology development, all knowledge is assumed to be manifest and only extracted from experts in the field. This research extends the human-computer interactions (HCI) and HMI paradigms to the study of cognitive interactions of humans and intelligent machines in systemic decision task processes.

The foundational BoK for HI-MI decision governance must be synthesised from expert knowledge in the disparate domains of systems governance, knowledge governance, data governance, AI, decision theory, socio-technical systems as well as HCI and HMI. In order to synthesise these disparate bases of knowledge, a mixed research method is followed with quantitative text mining and content analyses being overlaid on a qualitative grounded theory analysis framework. The knowledge generation ontology development methodology for this study, shown in Figure 4, is summarised in the following steps:

1 data gathering: create corpus of peer reviewed journal articles of the identified knowledge domains

2 concept extraction: perform text mining for concept extraction to identify structural commonalities and differences in the literature corpus

3 open coding: using the identified structural commonalities and differences, conduct open coding in grounded theory analysis in order to establish concept classes/categories for the HI-MI decision governance BoK

4 taxonomy development: follow ontology design method and specifications to develop taxonomy classes/categories

5 content analysis: perform content analysis to identify taxonomical relationships within and between structural relationships

6 axial coding: using the taxonomical relationships, conduct axial coding in grounded theory analysis to establish axiomatic relationships

7 ontological relationships: follow ontology design method and specifications to develop ontological relationships

8 content refinement: perform content refinement to refine taxonomical structure and axiomatic relationships

9 selective coding: apply grounded theory selective coding to refine taxonomical structure and axiomatic relationships

10 ontology refinement: follow ontology design method to conduct taxonomy-ontological refinement

11 evaluation: validate the foundational ontology against the developed foundational HI-MI theoretical BoK.

Now, the grounded theory open coding must specify how saturation is achieved. Saturation is a key term in qualitative research and can be found in various forms, with its origination being theoretical saturation as developed in grounded theory (Guest et al., 2006). Other variations of the concept for other qualitative methods include data saturation (Francis et al., 2010; Guest et al., 2006), thematic saturation (Guest et al., 2006) and in some cases simply saturation (Starks and Trinidad, 2007), as noted in the history of saturation (O'Reilly and Parker, 2012).

Despite the significance of the term 'saturation' and its applicability within grounded theory-based study, there are some misconceptions about how to achieve it. There appears to be no strict standard rules, criteria, or practical guidance on how to attain saturation. Glaser and Strauss (1967) first outlined saturation as the point at which "…no additional data are being found whereby the researcher can develop properties of the category. As the researcher sees similar instances over and over again, the researcher becomes empirically confident that a category is saturated…when one category is saturated, nothing remains but to go on to new groups for data on other categories and attempt to saturate these categories also."

Further, Bowen (2008) noted that, data saturation entails bringing new data continually into the study until the data set is complete, as indicated by data replication or redundancy. In other words, saturation is reached when the researcher gathers data to the point of diminishing returns, when nothing new is being added. Charmaz (2003) explained that saturation calls for fitting new data into categories already devised. For their part, Morse and Field (1995) pointed to the purpose of data saturation as "…saturating data ensures replication in categories; replication verifies and ensures comprehension and completeness." Therefore, in grounded theory, the notion of saturation does not refer to the point at which no new ideas emerge, rather means that categories are fully accounted for, the variability between them are explained, and the relationships between them are tested and validated and thus a theory can emerge (Green and Thorogood, 2004).

Another known question about data saturation often identifies the 'quantity' or 'numbers' on data collection and how that impacts overall saturation. In fact, this can vary from one research to another and even within the same research from one theme or category to another. There are two key considerations that guide the sampling methods in qualitative research – appropriateness and adequacy (Morse and Field, 1995). Marshall (1996) argued that the researcher should be pragmatic and flexible in their approach to sampling and that an adequate sample size is one that sufficiently answers the research question. In this sense, generalisability is not sought by the researcher and the focus is less on sample size and more on sample adequacy (Bowen, 2008). Bowen (2008) also argues that adequacy of sampling relates to the demonstration that saturation has been reached, which means that depth as well as breadth of information is achieved. Thus, the quality of data over quantity or numbers must be prioritised. Researchers must always ensure that the data source is valid and collected data possess high standards as well as quality to uphold the research potency to maintain the soundness and robustness of the study.

Despite all the debates and arguments, saturation as a concept still remains nebulous, and the process lacks systemisation (Bowen, 2008). Therefore, the best way to formally maintain this integral part of any qualitative research is not just merely mentioning in a single statement that saturation is achieved, but clearly, explaining how the saturation is achieved along with any related issues or limitations. Precise documentation must also be provided for a clear picture of attaining saturation. Researcher(s) must also state what systematic checks and quality assurances are made in obtaining saturation. To address the saturation in this study, three tiers of assessments are made:

1 source

2 building a concept dictionary

3 identifying the specifications for open coding.

Source validity identifies any limitations or issues regarding the data source that may pose a concern for quality of data resulting in a negative impact to the overall research. On the other side, to manage, organise and analyse collected documents, primarily for open coding, a data dictionary in the form of a concept dictionary was created within Microsoft Word with some reasonable parameters such as:

1 corpus title

2 author(s)

3 publication year

4 publication source

5 keywords

6 primary research question(s),

7 secondary research question(s)

8 open categorical coding theme

9 axial relationships theme.

The primary goal for this concept dictionary was to extract themes or concepts from compiled data. The secondary goal of this concept dictionary was to ensure whether a particular theme or concept or categories are fully accounted for to achieve saturation.

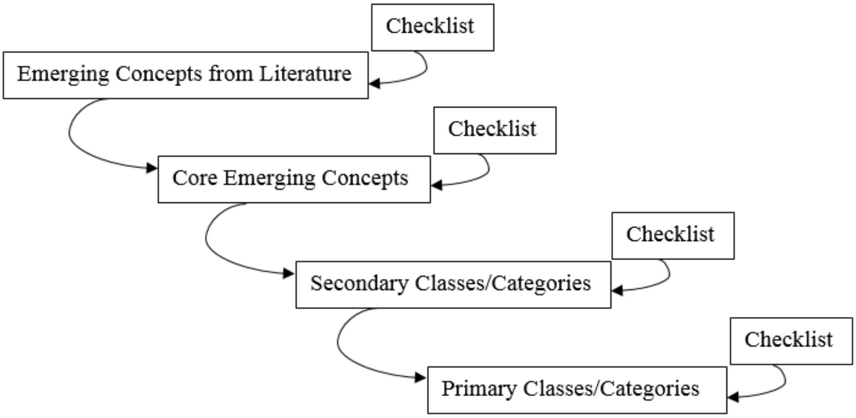
The purpose of open coding is to arrange any qualitative data in a more manageable format for categorising and to assist with further analysis into axial and selective coding. The term ‘code’ entails a named concept. The objective of coding is to produce codes that relate directly to the original authors’ conceptual perspectives. Codes also permit the assessment of saturation; that is completeness of the corpus in breadth and depth. Once the document corpus is assembled, work proceeds to open coding in which the literature is comparatively decomposed into natural conceptual categories. After completing the concept dictionary, criteria in Table 1 (Mahmud, 2018) are specified for open coding.

Table 1 Open coding specifications

Phases	*Goals and steps*	
Phase 1	Goal 1	To identify emerging concepts from relevant literature.
Steps for identifying emerging concepts/categories	Step 1	Read papers.
	Step 2	Check for theme or concept implication.
	Step 3	Identify emerging concept classes/categories.
	Step 4	Document as emerging concept classes/categories.
Phase 2	Goal 2	To identify core-emerging classes/categories.
Steps for identifying core-emerging concepts/categories	Step 1	Look up for similar concepts and their consistency.
	Step 2	Cross-check for relevancy.
	Step 3	Identify and merge similar concepts.
	Step 4	Document as core-emerging concept classes/categories.
Phase 3	Goal 3	To identify secondary classes/categories.
Steps for identifying secondary classes/categories	Step 1	Identify core-emerging concept classes/categories to fit into secondary concept classes/categories.
	Step 2	Document as secondary category.
	Step 3	Documentation of relevant literature by paper title, lead author and year under secondary category.
Phase 4	Goal 4	To identify primary concept classes/categories.
Steps for identifying primary concept classes/categories	Step 1	Identify secondary concept classes/categories to fit into primary concept classes/categories.
	Step 2	Documentation by primary concept category.

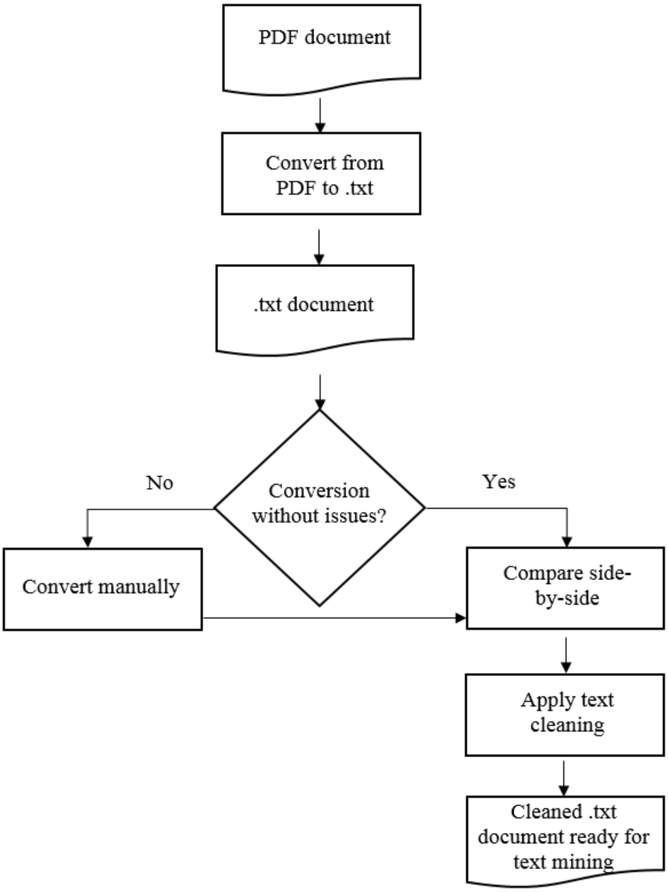
Based on the conditions and steps set in Table 1, literature relevant to similar themes are first sorted within secondary and then, eventually, under primary classes/categories. Figure 5 shows how primary classes/categories evolved from the concept dictionary.

Figure 5 Schematic approach for identifying categories



Collected data are gathered into various secondary categories that eventually fell into different primary or top categorical themes. In each secondary category, the number of related literatures for saturation varied. Before conducting data analysis, the systematic approach depicted in Figure 6 is followed to convert PDF files of the literature corpus into cleaned text format. Issues encountered during text cleaning are also identified for the sake of further validation.

Figure 6 Flow diagram from PDF to text mining ready document



4 Necessary conditions in the ontology and BoK

Both inductive reasoning (Evans and Over, 1996; Harman, 1999; Heit, 2000) and abductive reasoning (Peirce, 1878; Paul, 1993; Aliseda, 1997; Magnani, 2001; Lipton, 2004) begin with observations. Inductive reasoning assumes or constrains the reasoning space to complete information, whereas, abductive reasoning relaxes the assumption of complete information. Conversely, the taxonomic structure of ontology requires monotonic mutual exclusivity and exhaustiveness of complete information. The logic of the abductive-deductive grounded theory-based BoK development (Figure 4 right-hand side BoK development) versus the inductive-deductive ontology development (Figure 4 left-hand side ontology development) is that it counter balances the pure abductive arguments and deductive interpretations necessary in grounded theory supported BoK development with inductive-deductive logic necessary for establishment of the taxonomic and axiomatic structures in ontology design. That is, it forces proof of abductive-deductive knowledge theories by inductive-deductive logic.

Now, first analysing how the abductive-deductive logic holds good for the BoK development. Unlike inductive and deductive inferences, abductive reasoning can be specified by infinite constraints set by the research seeking various alternative solutions to a problem. As noted by Klarman et al. (2011) "…the space of abductive solutions can be in principle infinite, it is common to employ additional constraints to narrow it down, at least by excluding obviously unacceptable solutions." These constraints delimit the reasoning space for complete information and act as necessary or minimal conditions to uphold an abductive explanation, in this research, the abductive explanation of the HI-MI decision governance BoK. Based on Aliseda's (1997) abduction requirements, elsewhere identified as the most intuitive and universal requirements (Klarman et al., 2011), Elsenbroich et al. (2006) affirmed on the similar constraints (as listed below) to employ and support the integration of non-monotonic abductive reasoning into the deductive monotonic ontology design:

1. Consistency: this criterion allows only consistent solutions by discarding solutions inconsistent with the knowledge-base. In this study, it means to ensure whether taxonomic classes, their relationships and overall ontological structure are consistent with the foundational BoK. The consistency requirement is checked by Fluent Editor.
2. Minimality: the minimality criterion checks that solutions do not contain any irrelevant or superfluous information by not abducing more than what is necessary. Minimality condition may be considered as a sufficient one to explain a solution, however, can be extended to a necessary condition by deploying even stronger assertion on top of the minimal one.
3. Relevancy: this criterion checks further whether a solution is relevant or not in conjunction with the knowledge-base. A query must not entail the solution by its own unless engaging the union of BoK. A joint BoK and query should entail a solution to be relevant. Relevancy check prevents accepting ad hoc solutions that avoid problems itself rather solving it (Klarman et al., 2011).
4. Explanatoriness: to ensure developed ontology prevails explanations by taking into account both relevancy and consistency. Explanations must be relevant and consistent with the BoK. This criterion is also tested by Fluent Editor checks.

The second thing to clarify is the deductive proof/interpretations of the aforementioned abductive explanations. This analysis confirmed axiomatic support from the abductive logic programming (ALP) context (Esposito et al., 1996; Lamma et al., 2000). Lamma et al. (2000) provided an extension of logic programming (LP) to perform abductive reasoning, later supported by an algorithmic update (Esposito et al., 2007). ALP is an extension of LP to support abductive reasoning with logic programs that incompletely describe their problem domain (Esposito et al., 2007). By utilising any relevant tool, a minimal set of axioms can be identified to be inserted into a knowledge-base for a certain entailment to hold in abduction (Bada et al., 2008). In this research, Fluent Editor is used to insert and manipulate a minimal set of axioms.

Gruber's (1995) ontology design criteria impose necessary conditions of ontology design. Aliseda's (1997) and Elsenbroich et al.'s (2006) necessary constraints on abductive reasoning establishes logical supports by delimiting problem space for consistency, minimality, relevancy and explanatoriness. Further, a minimal set of axioms in ALP provides additional support for deductive interpretations. By integrating Gruber's (1995) ontology design criteria with necessary abductive constraints and axiomatic support, the foundational HI-MI decision governance ontology satisfies required necessary conditions as shown in Figure 4. Table 2 summarises the necessary conditions to support developed foundational ontology.

Table 2 Necessary conditions

Purpose	*Necessary conditions*
Ontology design (Gruber, 1995)	Clarity
	Coherency
	Extensibility
	Minimal encoding bias
	Minimal ontological commitment
Abductive constraints (Aliseda, 1997; Elsenbroich et al., 2006)	Consistency
	Minimality
	Relevancy
	Explanatoriness

Now that both abductive explanations and deductive proof are explained, we may consider the ontological structure as a set {A, D} which provides a deductive structure D and abductive meaning A. The foundational ontology provides primarily a deductive structure D with minimal abductive explanation A from the associated BoK. Additional deductive structure D_S will be achieved in subsumed core reference, domain and knowledge application ontologies through addition of refined subsumed minimal abductive explanations A_S. Full deductive structure plus abductive explanation $\{A, D\} \subset \{A_S, D_S\}$ can be derived only from examination of the full foundational, core reference, domain and application ontological structure.

5 Verification

Ontology verification checks the correctness of building of the ontology following ontology design criteria. The resultant ontology is verified by Fluent Editor that uses Gómez-Pérez's (1996, 1999, 2001) criteria such as consistency, completeness, conciseness, expandability and sensitiveness for evaluating and verifying taxonomies and ontologies. As explained before and shown in Table 2, the necessary conditions are taken into account to explain deductive structure and inductive meaning in the ontological structure. Further, Fluent Editor is used to conduct the verification. Table 3 shows the listing of necessary conditions with verification criteria.

Table 3 Necessary conditions with verification criteria

Purpose	*Necessary conditions*	*Verification criteria*	*Verification meet*
Ontology design (Gruber, 1995)	Clarity Coherency Extensibility Minimal encoding bias Minimal ontological commitment	Conciseness Consistency Expandability Completeness Sensitiveness	By Fluent Editor using Gómez-Pérez's (1996, 1999, 2001) criteria
Abductive constraints (Aliseda, 1997; Elsenbroich et al., 2006)	Consistency Minimality Relevancy Explanatoriness		

6 Validation

Validation is an integral part of ontology development. This study addressed both short-term and long-term validations. Short-term validation is achieved in each phase of the research methodology summarised in Figure 4. As set forth earlier, in Phase 1, text mining is conducted for concept extraction. Open coding is performed in grounded theory for concept classes/categories. On the parallel side, following the suggested upper merged ontology (SUMO, 2017) ontological design method, taxonomy classes/categories are established. As a validation, established taxonomic classes/categories are checked to support by the grounded theory concept classes/categories. On the grounded theory BoK development side, it is cross-checked whether the concept classes/categories found by open coding are supported by the taxonomy classes/categories established following the SUMO ontological design method. The cross-validation is maintained in each phase of the methodology. This process thus, satisfies consistency and relevancy check with theoretical BoK. Long-term validation will be maintained by ontology refinements.

All ontologies are dynamic entities requiring revisions and refinements. As new knowledge emerges, all extensible ontologies must be refined to achieve long-term validation as well as to support extendibility. This long-term validation will conform Gruber's (1995) extendibility design criteria in ontology development.

7 Conclusions and future work

Ontology and its knowledge-base are interdependent. A knowledge-base must reference its ontology, but the ontology must reflect the existing state of knowledge. For developing HI-MI decision governance ontology, the existing collections of relevant knowledge must be synthesised from the domains of the general systems, governance, decision theory, socio-technical systems, human-machine interaction and AI. Further, a knowledge-base is a dynamic entity in a way that it changes with the addition of new knowledge. The only way to capture and build a knowledge-base for ontology design is by having an actual sample representative of the accessible population by sample design.

Long-term validation of ontology requires ontology refinement which is triggered by updating the existing BoK with the addition of new knowledge into the knowledge-base.

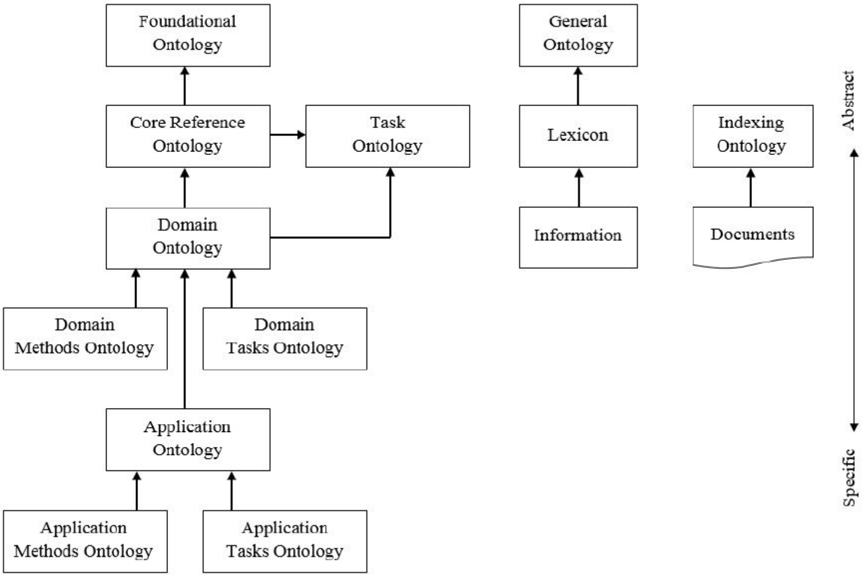
Unlike any other studies, ontological study/analysis enforces:

1. identifying problem space from core level
2. identifying all relevant domains required to build the taxonomic terms for better understanding the domain of discourse
3. establishing the inherent relationships among the taxonomic terms
4. relying on an expert reference-base or knowledge-base that can cross-validate the developed ontology.

On top of that, dynamic nature and requirement of ontology always triggers the updates with the addition of new knowledge to the KB. Thus, we can use the most up-to-date knowledge and also, extend the fundamental understanding of the domain using shared conceptualisation from various other domains. The thoroughness of ontological analysis makes an analysis rigor and mature to essentially benefit out of it.

It must be acknowledged that ontology and its development are not untested, however, is quite new in some domains regarding the overall philosophical perception, misconception, therefore its application in real-world. Moreover, the rationale of ontological studies and basis are sometimes quite uncompelling to the research community due to epistemological biases. Thus, it is not only the lack of a comprehensive framework for various levels of ontological development, but also not to offer a rigor, sound and systematic approach for any such quest. This paper offers readers to get a theoretical and practical aspects of ontological exploitation to have an in-depth knowledge on complex systems, essentially the views and the perspective of ontological studies to overcome system's nuance (answering the question – why ontology?).

Figure 7 Ontology types/levels



There is much ontology out there; however, not based on an integrative framework that connects all levels of ontological development. Figure 7 gives us a broader view of ontology development process. This paper presented an integrative and parallelistic approach of building top/foundational to application level ontologies. Building ontology in one level (say, for an example, application level) for a domain of discourse will neither lessen system's nuance or any such challenges, nor be able to grasp the complete knowledge or understanding.

Ontology development took place in many areas, however, in discrete levels. This means, there are ontologies out there, but most of them are in the application level. Without having a top-down approach (top → core-reference → domain → application), there is no way we can ensure both the interoperability and extendibility of knowledge. Therefore, the missing connections among top → core-reference → domain → application ontologies need to be investigated. This paper provides a systematic approach for developing top to application level ontologies. From a system's level, this is urgent and necessary to address and this paper sheds lights on it.

Finally, this paper demonstrated both the general and specific approach toward developing a general HI-MI decision governance theory and BoK. The presented systematic analysis proves the methodological soundness and strength for further development of various other levels of ontology. There is already a top/foundational ontology developed based on this systematic approach, another core-reference ontology is underway and those ontologies will be presented in future release. Having the top/foundational ontology constructed based on the given methodology, along with the verifications and validations as well as supportive other evidences, subsequent future work is laid for core-reference, domain and application level ontological development.

References

Aliseda, A. (1997) *Seeking Explanations: Abduction in Logic, Philosophy of Science and Artificial Intelligence*, PhD thesis, ILLC, University of Amsterdam.

Bada, M., Mungall, C. and Hunter, L. (2008) 'A call for an abductive reasoning feature in owl-reasoning tools toward ontology quality control', in *Proceedings of the 5th International Workshop OWL: Experiences and Directions (OWLED'08)*, Karlsruhe.

Bowen, G. (2008) 'Naturalistic inquiry and the saturation concept: a research note', *Qualitative Research*, Vol. 8, No. 1, pp.137–152.

Chandrasekaran, B., Josephson, J.R. and Benjamins, V.R. (1999) 'What are ontologies, and why do we need them?', *IEEE Intelligent Systems*, Vol. 14, No. 1, pp.20–26.

Charmaz, K. (2003) 'Grounded theory: objectivist and constructivist methods', in Denzin, N.K. and Lincoln, Y.S. (Eds.): *Strategies for Qualitative Inquiry*, 2nd ed., Sage Publications, Thousand Oaks, CA.

Cotter, T. (2015) 'Research into the governance structure needed to integrate the dominant design methodologies', in *Proceedings of the 2015 Annual ASEM Conference*, Indianapolis, Indiana, USA, 7–10 October.

Dong, H., Hussain, F.K. and Chang, E. (2011) 'A context-aware semantic similarity model for ontology environments', *Concurrency Computation: Practice and Experience*, Vol. 23, No. 5, pp.505–524.

Elsenbroich, C., Kutz, O. and Sattler, U. (2006) 'A case for abductive reasoning over ontologies', in *Proceedings of the OWLED'06 Workshop on OWL: Experiences and Directions*, Athens, Georgia, USA, 10–11 November.

Esposito, F., Ferilli, F., Basile, T.M.A. and Mauro, N.D. (2007) 'Inference of abduction theories for handling incompleteness in first-order learning', *Knowledge Information System*, Vol. 11, No. 2, pp.217–242.

Esposito, F., Lamma, E., Malerba, D., Mello, P., Milano, M., Riguzzi, F. and Semeraro, G. (1996) 'Learning abductive logic programs', in *Proceedings of the ECAI96 Workshop on Abductive and Inductive Reasoning*, Budapest, Hungary, pp.23–30.

Evans, J.S.B.T. and Over, D.E. (1996) *Rationality and Reasoning*, Psychology Press, Hove.

Francis, J., Johnston, M., Robertson, C., Glidewell, L., Entwistle, V., Eccles, M.P. and Grimshaw, J.M. (2010) 'What is adequate sample size? Operationalizing data saturation for theory-based interview studies', *Psychology and Health*, Vol. 25, No. 10, pp.1229–1245.

Gheorghe, A.V., Vamanu, D.V., Katina, P.F. and Pulfer, R. (2018) *Critical Infrastructures, Key Resources, Key Assets: Risk, Vulnerability, Resilience, Fragility, and Perception Governance*, Springer, Cham.

Glaser, B. and Strauss, A. (1967) *Discovery of Grounded Theory: Strategies for Qualitative Research*, Aldine Publishing Co., Chicago.

Gómez-Pérez, A. (1996) 'A framework to verify knowledge sharing technology', *Expert Systems with Application*, Vol. 11, No. 4, pp.519–529.

Gómez-Pérez, A. (1999) 'Evaluation of taxonomic knowledge on ontologies and knowledge-based systems', in Gaines, B., Kremer, R. and Musen, M. (Eds.): *12th Knowledge Acquisition for Knowledge-Based Systems Workshop (KAW'99)*, 6.1, pp.1–18, Banff, Canada.

Gómez-Pérez, A. (2001) 'Evaluation of ontologies', *International Journal of Intelligent Systems*, Vol. 16, No. 3, pp.391–409.

Green, J. and Thorogood, N. (2004) *Qualitative Methods for Health Research*, Sage, London.

Gruber, T.R. (1993) 'A translation approach to provide ontology specification', *Knowledge Acquisition*, Vol. 5, No. 2, pp.199–220.

Gruber, T.R. (1995) 'Toward principles for the design of ontologies used for knowledge sharing', *International Journal of Human-Computer Studies*, Vol. 43, Nos. 5–6, pp.907–928.

Guest, G., Bunce, A. and Johnson, L. (2006) 'How many interviews are enough? An experiment with data saturation and variability', *Field Methods*, Vol. 18, No. 1, pp.59–82.

Harman, G. (1999) *Reasoning, Meaning, and Mind*, Oxford University Press, Oxford.

Heit, E. (2000) 'Properties of inductive reasoning', *Psychonomic Bulletin & Review*, Vol. 7, No. 4, pp.569–592.

Keating, C.B., Katina, P.F. and Bradley, J.M. (2014) 'Complex system governance: concept, challenges, and emerging research', *International Journal of System of Systems Engineering*, Vol. 5, No. 3, pp.263–288.

Keenan, J. and Aggestam, M. (2001) 'Corporate governance and intellectual capital: some conceptualizations', *Corporate Governance: An International Review*, Vol. 9, No. 4, pp.259–275.

Klarman, S., Endriss, U. and Schlobach, S. (2011) 'ABox abduction in the description logic ALC', *Journal of Automated Reasoning*, Vol. 46, No. 1, pp.43–80.

Lamma, E., Mello, P., Milano, M., Riguzzi, F., Esposito, F., Ferilli, S. and Semeraro, G. (2000) 'Cooperation of abduction and induction in logic programming', in Kakas, A. and Flach, P. (Eds.): *Abductive and Inductive Reasoning: Essays on their Relation and Integration*, Kluwer, Dordrecht.

Lipton, P. (2004) *Inference to the Best Explanation*, 1st ed., 1991, expanded 2nd ed., 2004, Routledge, London.

Magnani, L. (2001) *Abduction, Reason, and Science: Processes of Discovery and Explanation*, Kluwer Academic Publishers, New York.

Mahmud, F. (2018) *Human-Intelligence and Machine-Intelligence Decision Governance Formal Ontology*, PhD dissertation, Old Dominion University.

Mahmud, F. and Cotter, T. (2017) 'Human-intelligence/machine-intelligence decision governance: an analysis from ontological point of view', in *Proceedings of the International Annual Conference of the American Society for Engineering Management*, Huntsville, Alabama, 18–21 October.

Mahmud, F. and Zahedi, Z. (2018) 'Exploiting ontology – understanding a domain of discourse in engineering management', in *Proceedings of the ASEM 2018 International Annual Conference*, Coeur d'Alene, ID, 17–20 October.

Marshall, M. (1996) 'Sampling for qualitative research', *Family Practice*, Vol. 13, No. 6, pp.522–525.

Mittal, S., Diallo, S. and Tolk, A. (2018) *Emergent Behavior in Complex Systems Engineering: A Modeling and Simulation Approach*, John Wiley & Sons, Inc, New York.

Morse, J. and Field, P. (1995) *Qualitative Methods for Health Professionals*, 2nd ed., Sage, Thousand Oaks, CA.

Noy, N.F. and McGuinness, D.L. (2001) *Ontology Development 101: A Guide to Creating Your First Ontology* [online] https://protege.stanford.edu/publications/ontology_development/ontology101.pdf (accessed 15 July 2018).

O'Reilly, M. and Parker, N. (2012) ''Unsatisfactory saturation': a critical exploration of the notion of saturated sample sizes in qualitative research', *Qualitative Research*, Vol. 13, No. 2, pp.190–197.

Paul, G. (1993) 'Approaches to abductive reasoning: an overview', *Artificial Intelligence Review*, Vol. 7, No. 2, pp.109–152.

Peirce, C.S. (1878) 'Deduction, induction, and hypothesis', *Popular Science Monthly*, Vol. 13, pp.470–482.

Starks, H. and Trinidad, S.B. (2007) 'Choose your method: a comparison of phenomenology, discourse analysis, and grounded theory', *Qualitative Health Research*, Vol. 17, No. 10, pp.1372–1380.

Stout, M. and Love, J.M. (2015) 'Relational process ontology: a grounding for global governance', *Administration & Society*, Vol. 47, No. 4, pp.447–481.

SUMO (2017) *IEEE Standard Upper Ontology* (IEEE SUO) [online] http://www.ontologyportal.org (accessed 1 May 2018).

Uschold, M. and King, M. (1995) 'Towards a methodology for building ontologies', in Skuce, D. (Ed.): *IJCAI'95 Workshop on Basic Ontological Issues in Knowledge Sharing*, pp.6.1–6.10, Montreal, Canada.

Weimer, J. and Pape, J. (1999) 'A taxonomy of systems of corporate governance', *Corporate Governance: An International Review*, Vol. 7, No. 2, pp.152–166.