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Toward data-driven idea generation: Application of Wikipedia to morphological analysis☆

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ABSTRACT

The generation of new and creative ideas is vital to stimulating innovation. Morphological analysis is one appropriate method given its objective, impersonal, and systematic nature. However, how to build a morphological matrix is a critical problem, especially in the big data era. This research focuses on Wikipedia's case-specific characteristics and well-coordinated knowledge structure and attempts to integrate the platform with morphological analysis. In details, several methodological options are explored to implement Wikipedia data into morphological analysis. We then propose a Wikipedia-based approach to the development of morphological matrix, which incorporates the data on *table of contents*, *hyperlinks*, and *categories*. Its feasibility was demonstrated through a case study of drone technology, and its validity and effectiveness was shown based on a comparative analysis with a conventional discussion-based approach. The methodology is expected to be served as an essential supporting tool for generating creative ideas that could spark innovation.

1. Introduction

Innovation has been a central issue in both academia and practice. The general definition of innovation is discussed in numerous research studies. Evangelista et al. (1998) defined innovation as a process from research to invention and then a diffusion of a new technique. A study by Drucker (1985) defined as "the act that endows resources with a new capacity to create wealth". In recent years, numerous scholars emphasized the importance of generating creative ideas in achieving such an innovation (Girotra et al., 2010; Rietzschel et al., 2014) and further proposed the notion that creative and innovative ideas originate from the right combination of disparate bodies of existing knowledge (Björk and Magnusson, 2009; Dosi, 1982; Geschka, 1983; Nakamura et al., 2015; Schilling and Green, 2011; Ward, 2004).

Morphological analysis has been particularly employed as a prominent tool for generating new ideas. It is a method that leads to structured inventions by determining all possible alternatives for solving a certain problem (Wissema, 1976; Yoon and Park, 2005; Geum et al., 2016). This technique has two strong advantages for idea generation. First, morphological analysis decomposes a complex system into parts and systematically rearranges combinations to generate ideas. This can be considered a "combinative" characteristic of the technique that sparks an abundant supply of creative ideas. Second, morphological analysis breaks down the target subject and reconstructs them to explore unprecedented structures. This can be considered an "inventive" characteristic of the technique that explores many different novel ideas, thus providing possible solution options for a given context.

Despite its popularity, one innate shortcoming of morphological analysis must be solved: the involvement of human subjectivity. The entire process of decomposing and restructuring into new knowledge can exist in the first place only if the morphological matrix is designed properly and specifically. This preprocessing step is the most fundamental step when considering the notion of GIGO–short for garbage in, garbage out. Previous studies, however, handled the morphology building process in a qualitative manner that depended on experts' opinions. Regardless of their advantages in capturing high reliability and validity, the involvement of human judgment was subject to numerous cognitive biases that could subsequently lead to a decrease of team performance and serious misjudgments (Zec et al., 2015). Furthermore, the conventional participatory process can no longer be applied to recently emerged products or services, which are so complex

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that a concrete decomposition cannot be achieved solely by a handful of professionals. For these reasons, there is in need of a shift toward a data-driven methodology, which could offer more objective and automatic results.

Several attempts have been made to suggest a data-driven approach of conducting morphological analysis, and patent data was generally incorporated as the main data source (Lee et al., 2007; Yoon et al., 2008; Yoon et al., 2014). However, one of the major limitations was that they were restricted to a single knowledge source of patent. Although it is renowned for its high reliability and usefulness, patent data often could not ensure up-to-dated, non-technological, or case-specific idea generation. To address this limitation, Geum and Park (2016) suggested WordNet-based morphological analysis. Their study highlighted the hierarchical network structure of WordNet, which has the capability of analytic and objective morphology development. However, WordNet was still subject to data rigidity and lacking domain-specific knowledge.

In response, this paper proposes a novel method of data-driven morphology building process using Wikipedia data. Wikipedia is a massive online repository of collective intelligence. The utilization of Wikipedia can be an excellent way to address the rigidity of WordNet. In terms of practicability, Wikipedia contains information from a wide range of fields and expands the data set to a new boundary. Unlike WordNet, Wikipedia offers a significant amount of case-specific knowledge that could better stimulate more specialized and practical idea generation. In terms of flexibility, Wikipedia provides hierarchical relationships of concepts, which enable a coherent matrix development of morphological analysis.

One thing to note is that the objective of this research is neither to propose the most effective method of developing creative ideas nor to supersede conventional idea generation techniques. The approach is rather a heuristic process model, attempted to demonstrate the key role of Wikipedia in morphology building step for ensuring conceptual breadth and facilitating creativity. The remainder of this research is organized as follows. Section 2 illustrates how the research of creative idea generation and morphological analysis has been previously carried out. Then, Section 3 describes the types of Wikipedia information to apply in the development of a morphological matrix and offers several alternatives to achieving this objective. With this background, we propose a research framework of constructing a Wikipedia-based morphological matrix in Section 4. Section 5 demonstrates the feasibility of our approach through the illustrative case study of drone technology. Section 6 further shows its validity and effectiveness based on a comparative analysis with a conventional discussion-based approach. Lastly, Section 7 discusses the intrinsic shortfalls of applying Wikipedia data in morphological analysis.

2. Related studies

2.1. Generating creative ideas

Generating new ideas has been a constant concern. A considerable literature has, thus, endeavored to address novel methods of idea generation. Starting with Osborn's brainstorming (Osborn, 1957), diverse idea generation techniques came into existence, including brainwriting, checklists, and synectics (Geschka, 1983; Ivanov and Cyr, 2014; VanGundy, 1981). They all made a tacit assumption: *quantity breeds quality* (Rietzschel et al., 2014). In other words, these techniques have assumed that as more ideas are created, the greater the possibility that creative ideas are found among them (Diehl and Stroebe, 1987; Girotra et al., 2010). As suggested by Shah et al. (2003), idea generation methodologies are classified into two primary groups: intuitive and logical. Intuitive methods are divided into germinal, transformational, SMAPER, progressive, C-sketch, organizational, fishbone diagram, and hybrid. Logical methodologies are divided into history-based methods and analytical methods such as TRIZ.

However, in recent years, the quality of the ideas has been questioned (Girotra et al., 2010; Rietzschel et al., 2014). Most studies underlined the concept of creativity as improving the quality (Rietzschel et al., 2014) and began to facilitate this improvement in idea generation process. Most studies demonstrated in a qualitative manner. For instance, Girotra et al. (2010) proposed the hybrid structure-in which individuals first work independently and then work together -and identified the structure's superior performance in terms of both quantity and quality. Rietzschel et al. (2014) applied a new brainstorming experiment and demonstrated that ideas became more creative as problems narrowed and instructions became more creative. In contrast, several studies attempted to demonstrate the improvement of quality in a quantitative manner. If a quantitative approach is taken, what is the best scale that determines a creative idea? According to Simonton (2013), the simplest but most useful answer is to treat criteria as dichotomous features. For example, a creative idea is original, rather than unoriginal, and useful, rather than useless. However, a definitional disagreement regarding the concept of creativity is inevitable given its subjective and versatile characteristics. Some research considered that creative ideas are both original and feasible (Diehl and Stroebe, 1987; Rietzschel et al., 2014; Sternberg, 1985). Other studies highlighted the concept of interventions during the generation process and demonstrated that ideas derived in the face of greater obstacles are considered more creative (Ward, 2004). Boden (2004) offered three criteria of novel, valuable, and surprising. As shown, the subjective concept of creativity was described through other subjective notions, such as original, novel, and valuable.

More recent studies focused on the methodology itself that generates new and creative ideas, and many of those stressed the underlying concept that creative ideas are crafted from existing knowledge by identifying novel combinations of previously separated ideas or concepts (Björk and Magnusson, 2009; Dosi, 1982; Geschka, 1983; Nakamura et al., 2015; Schilling and Green, 2011; Ward, 2004). In other words, a method that can systematically combine valuable knowledge from novel data sources is expected to generate creative ideas.

2.2. Data-driven morphological analysis

Morphological analysis is the study of basic forms or patterns of a thing (Ritchey, 2011). When viewed from the perspective of *totality of things* (Zwicky, 1957), a certain object can be divided into multiple parts, and different arrangements of those parts could conform to create different wholes. The decomposition can be organized into a table, so-called morphological matrix, composed of dimensions and values. A conventional example of a morphological matrix is shown in Table 1.

As an illustration, an unmanned aerial vehicle (UAV)-commonly known as drone-can be decomposed into four dimensions: body, sensors, actuators, and software. Generally, the body design of small UAV has 4 propelled rotors and is called quadcopter. If the body changes from 4 to 8 rotors, the UAV is an octocopter and serves a very different purpose than that of a quadcopter. Apparently, every dimension includes more than one value; for example, the body dimension comprises four, six, and eight rotor designs. When considering that a UAV is a

Table 1
Morphological matrix example for textile wet-processing system (Jones, 1976).

Textile additive	Fibre substrate	Process medium	Additive fibre mechanism
Dyestuff	Protein	Aqueous	Substantive
O.B.A.	Cellulose	Aqueous solution	Diffusion
Finish	Nylon	Organic solvent	Precipitation
Antistat	Polyester	Air gas vacuum	Reactive

combination of one value per dimension, what happens if every dimension includes 5 value options? The number of configurations increases exponentially to 625 (5 × 5 × 5 × 5) combinations. Because a small change in a value could lead to a large difference in a whole, each and every combination should be considered a candidate for creative ideas that may ultimately lead to an innovation (Zwicky, 1957).

According to Ritchey (2005), morphological analysis was first introduced in the field of biology and was used to generalize the combinatorial logic of the biological structure of organic bodies. Then, Zwicky (1957) proposed a generalized morphological analysis in the late 1940s that has been applied in a wide variety of scientific disciplines, including product planning (Geschka, 1983), technological forecasting (Jones, 1976), and futures study (Ritchey, 2005). However, such preliminary research was generally conducted in a qualitative manner, and some scholars underlined the limitations of an expert's subjectivity and lacking creativity. According to Zec et al. (2015), human bias was considered a critical bottleneck for effective collaboration for developing morphological matrix.

To address this issue, several quantitative studies have been conducted. Lee et al. (2007) proposed a new IT-based service concept generation method using patent analysis. Yoon et al. (2008) used information from product manuals and patent documents to develop a morphological analysis-based technology roadmap. Yoon et al. (2014) developed technology morphology and product morphology on the basis of patent information. However, the application of patent data is deemed unsuitable of the following reasons. First, there exist a time-lag between patent application date and patent grant date. Such an intrinsic drawback of patents cannot fully ensure up-to-dated knowledge source when constructing a morphological matrix and generating novel and non-obvious ideas. In fact, this is particularly critical considering today's fast-paced and ever-changing business environment. Second, patents are excellent proxy measures for technology, but they cannot be directly applied to non-technological and case-specific idea generation.

A recent study by Geum and Park (2016), in response, attempted to integrate WordNet into morphological analysis. WordNet was considered an excellent alternative to patent data (Geum and Park, 2016) since it is a large electronic database that forms a semantic network of words, interconnected through relations among meanings (Poli et al., 2010). The meronym/holonym relations and the hyponym/hypernym relations are employed to build a morphological matrix by providing dimensions and values. However, WordNet was still subject to knowledge rigidity, and the approach had a major limitation in terms of lacking domain-specific knowledge.

3. Idea creation using Wikipedia

3.1. Wikipedia as a good remedy for morphological analysis

This study proposes a Wikipedia-based morphological analysis to address the limitations of prior studies. Wikipedia is a massive online repository of collective intelligence, which allows almost anyone to become contributors to information development (Milne, 2007; Mihalcea and Csomai, 2007). In fact, Wikipedia is the largest, fastest growing encyclopedia in the world (Wang and Domeniconi, 2008; Milne, 2007). It has been widely accepted as an alternative data source for WordNet and has received significant attention from computer science research community in recent years. For instance, Wikipedia was utilized to solve various natural language processing tasks, such as semantic relatedness (Milne, 2007), text classification and clustering (Hu et al., 2009; Wang and Domeniconi, 2008), text identification (Hassan et al., 2012; Joorabchi et al., 2015), and topic modeling (Allahyari and Kochut, 2016; Ciglan and Nørvåg, 2010).

Wikipedia's distinguished features are as follows: (1) extensive topic coverage; (2) up-to-dated context; (3) domain-specific description; and (4) rich semantics (Joorabchi et al., 2015; Strube and Ponzetto, 2006). Wikipedia holds millions of articles covering subjects in all areas of human knowledge and is continuously updated with new information (Joorabchi et al., 2015). In respect of idea generation, the most notable strength of Wikipedia is twofold: domain-specific concepts and coherent semantic relationships, including equivalence, hierarchical, and associative relations.

First, Wikipedia provides specialized and practical concepts (Strube and Ponzetto, 2006). An idea could be valued only if it has been transformed into practical reality, an application across a variety of contexts. When Wikipedia is incorporated in morphological analysis, its case-specific knowledge may improve the quality of input, thereby increasing the possibility of detecting novel and useful ideas. Second, rich semantic relationships allow for a systematic idea generation process. In terms of equivalence relations, Wikipedia offers alternative concepts, such as synonyms, acronyms, and common misspellings, of a certain concept through *redirect links*. For instance, *drone* includes a *redirect link* to *UAV*. Moreover, *disambiguation pages* resolves the conflict of articles having the same page titles by providing the list of concepts with identical names. The hierarchical relations of broader and narrower concepts are also demonstrated through *categories*. Every article is required to have at least one category, and these categories can be further categorized using other parent categories (Bunescu and Pasca, 2006). For example, *drone* is categorized in *robotics* and *emerging technologies*, and *emerging technologies* is further classified in *futurology* and *technology forecasting*. As is shown, higher-level concepts of a certain subject can be derived from *categories* page. Other than *categories*, certain pages such as *subcategories* and *pages in categories* provide useful hierarchical relations of the concept. Last but not least, associative relations are represented through *hyperlinks*. These relationships present the connections between the concepts that are closely related in a non-hierarchical fashion. *Drone*, for instance, is associated with the concepts of *antenna*, *analog-to-digital converter*, and *avionics*, and these terms constitute one of the sentences in the *communications* section of the *drone* article. In summary, Wikipedia can be a great complementary and valuable source for constructing a morphological matrix in idea generation, as listed in Table 2.

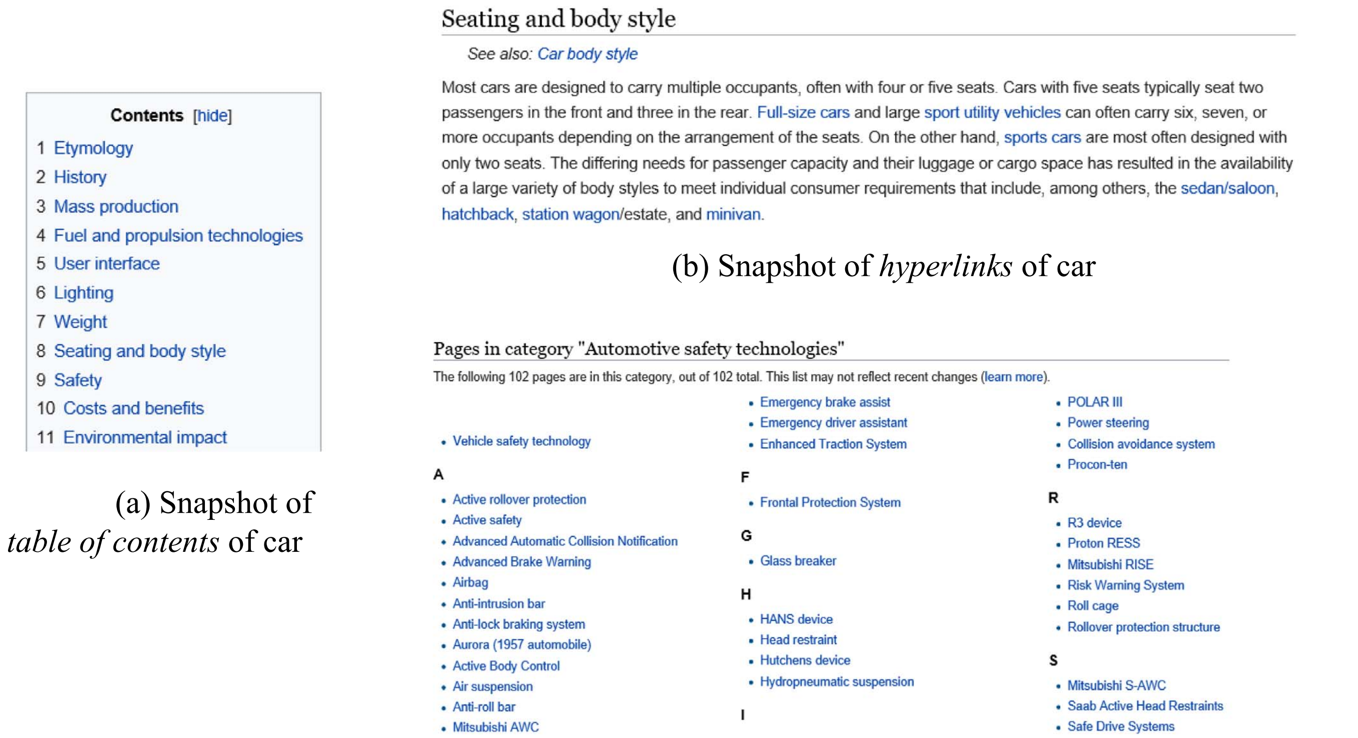
3.2. Preliminaries: how to apply Wikipedia to morphological analysis

Since there exist many different types of information in Wikipedia, this section thoroughly investigates the specific types, which could be useful for developing a morphological matrix. The information types to be investigated are *tables of contents*, *hyperlinks*, and *categories*, as shown in Fig. 1. Each type has its distinctive strengths and weaknesses, as shown in Table 3.

First, *table of contents* shows the summary of an article's contents, offering a clear overview of its structure. Such a feature allows easily and precisely obtaining the subject's composition information. Furthermore, various types of information are included in the list, and this may diversify input sources for matrix construction not only with technical but with non-technical contents, such as social, political and economic aspects. To understand the whole of a certain thing, one must grasp every aspect of it. The application of *table of contents* is thus

Table 2
Complementary characteristics of Wikipedia and a morphological matrix.

Advantage of Wikipedia	Strength in building a morphological matrix
Case-specific knowledge	- Offers specialized and practical knowledge, thereby increasing the possibility of detecting new and practical ideas
Semantic relationships between concepts	- Allows to decompose the subject into parts in automatic and systematic manner given its semantic relations



(a) Snapshot of *table of contents* of car

(b) Snapshot of *hyperlinks* of car

(c) Snapshot of *pages in categories* of automotive safety technologies

Fig. 1. Useful information types for morphological analysis.

powerful in dimension building process. The *table of contents* for “car”, for instance, offers a solid list of dimension candidates, including “fuel and propulsion technologies”, “user interface”, “lighting”, “weight”, “seating and body style”, and “safety”, as indicated in Fig. 2. The disadvantages, however, are its inconsistency and lacking contextual breadth. While the secret to the abundance of knowledge is collective intelligence, a handful number of editors – from expert scholars to casual readers – cannot create fully coherent and consistent article structures. The layouts are often different from one article to another. For example, some sections are composed of multiple concepts, like ‘fuel and propulsion technologies’ and ‘seating and body style’. Moreover, the sections included in *table of contents* are subject to a limited contextual breadth, causing incoherency in developing a morphological matrix. Such a setting is a serious challenge when developing morphological matrix for a general use. A supplementary discussion is required to better organize the matrix.

Second, *hyperlinks* represent domain-related concepts closely associated to the corresponding sections. In a situation where each article is composed of thousands of words, *hyperlinks* are useful indicators for selecting suitable concepts in developing the matrix. It not only allows users to effortlessly retrieve the most relevant information but also serves as informative descriptors of the subject page (West et al., 2015). Therefore, we could consider them as the target's relatively essential elements. They would be particularly valuable in value development in morphological matrix. The *hyperlinks* in the section of ‘seating and body style’, for instance, contain relevant concepts like “full-size cars”, “sport utility vehicles”, “sports cars”, “sedan/saloon”, “hatchback”, “station wagon”, and “minivan”. These subsidiary concepts could be assigned as values for “seating and body style dimension”, as shown in Fig. 3. As shown, the main advantage of using *hyperlinks* is that they ensure conceptual significance and conceptual relevance. However, some *hyperlinks* may yield too much details with arbitrary hierarchical information. Such excessive description and non-hierarchical nature are considered primary disadvantages of its application.

Third, *categories* provide all concepts above a certain concept; *pages in categories* provide all concepts below the concept; and *subcategories* provide concepts from one level below the concept. Such a categorical system offers navigational links to Wikipedia articles. This is a great source for supplementing both dimensions and values of morphological

Table 3
Summary of applicability to dimensions and values.

	Advantage	Disadvantage	Applicability to dimensions	Applicability to values
Table of contents	- Structured information - Information diversity	- Inconsistency - Limited contextual breadth	Very likely	Unlikely
Hyperlinks	- Conceptual significance - Conceptual relevance	- Excessive description - Non-hierarchical structure	Likely	Very likely
Categories	- Hierarchical structures - Contextual depth	- Excessive amount - Complex structure	Very likely	Very likely

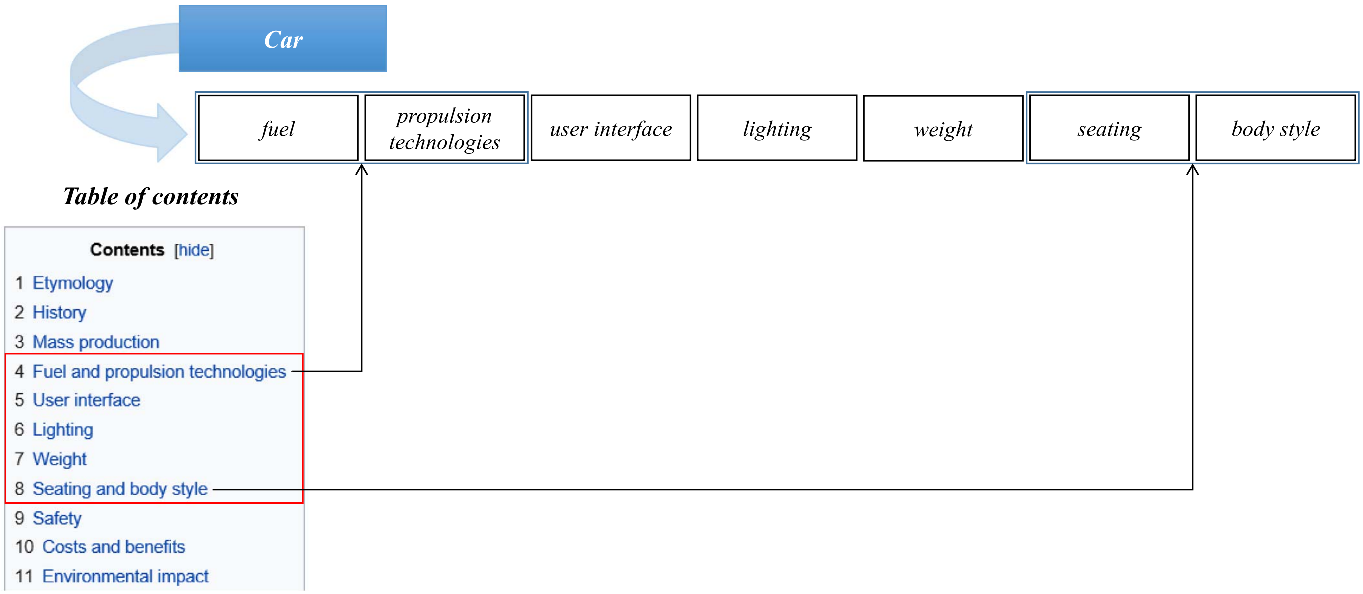


Fig. 2. Example of dimension building using *table of contents*.

matrix because both superordinate and subordinate concepts, which are related indirectly to the target subject, could be extracted based on their hierarchical relationship. Like the concepts of "alternative fuels" and "automotive lamps" in Fig. 4, *categories* yield a list of concepts that could potentially play intermediary roles for supplementing subsidiary concepts, supplied by *pages in categories*. Two different methods exist for such a value expansion, as illustrated in Fig. 4(a) and (b). The former uses a same-level concept; whereas, the latter uses a higher-level concept from *categories* in order to generate the subsidiary concepts from *pages in categories*. Furthermore, *subcategories* could be utilized for expanding the number of dimensions, as presented in Fig. 5. On the basis of dimensions constructed from the *table of contents*, *subcategories* could supplement additional concepts, including "automotive styling features", "car body styles", "car crime", and "car culture". However, there often exist an excessive number of concepts within *subcategories* and *pages in categories*. A group discussion is necessary to extract meaningful and relevant concepts. In addition, its proper application is quite difficult to achieve since *categories* provides quite complex and inconsistent conceptual structures.

Considering their advantages, the utilization of *tables of contents*, *hyperlinks*, and *categories* is a great starting point for developing a data-driven morphological matrix. This article determines how to construct a detailed yet concise matrix by offsetting their respective limitations. First, information in *table of contents* is used to extract only the interested sections and to develop the main compositions, or dimensions, of a target. This preliminary process reduces noise and creates a more diversified but integrated structure of a morphological matrix. Second, *hyperlinks* are informative descriptors, which includes domain-specific

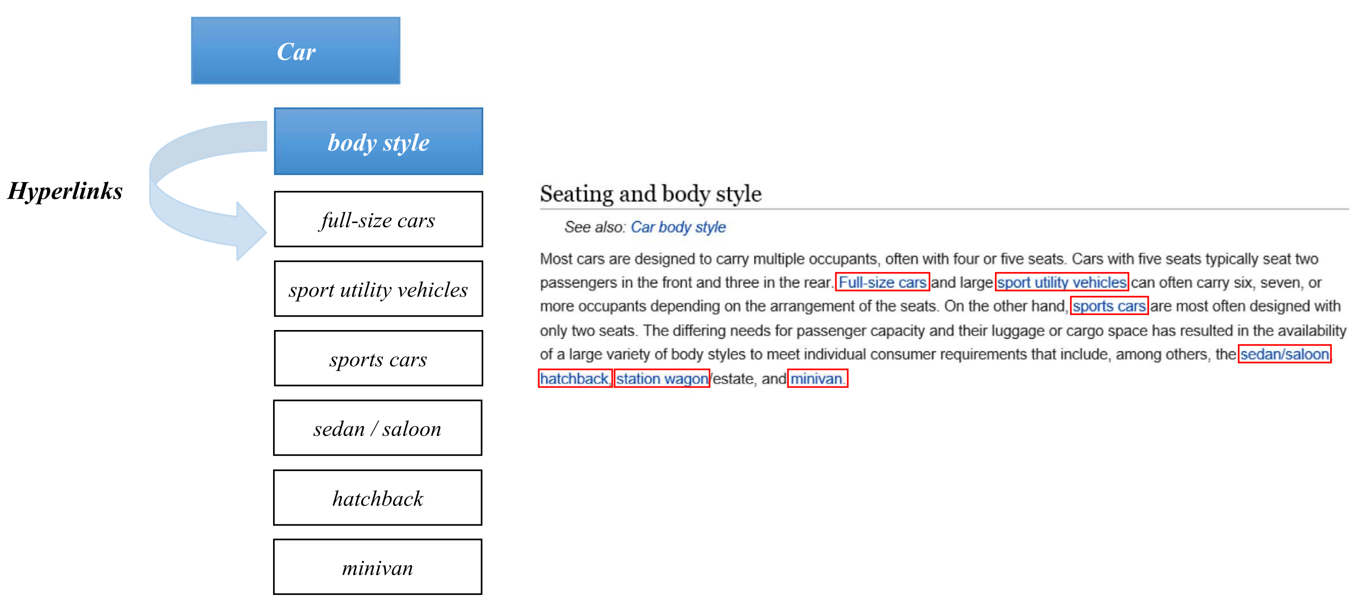
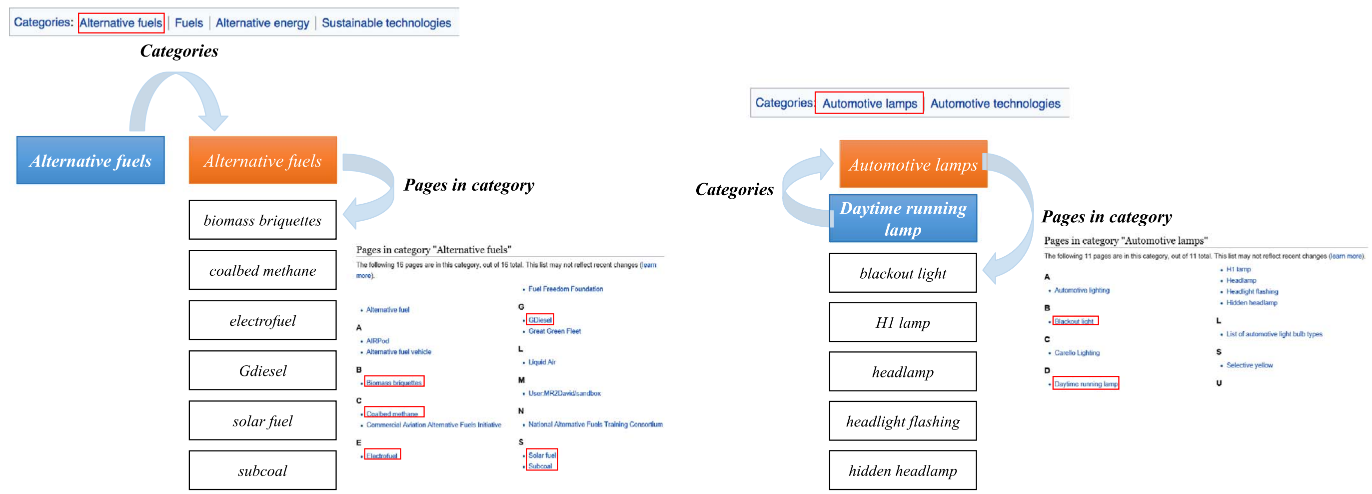


Fig. 3. Example of dimension building using *hyperlinks*.



(a): Supplementing values using same-level concept (b): Supplementing values using higher-level concept

Fig. 4. Example of expanding values using *categories*.

information highly related to dimensions. They serve as a great supplementing source of these corresponding dimensions; however, *hyperlinks* often cannot cover all associated concepts of a certain dimension. In order to ensure comprehensiveness and relativeness in value development, nouns or noun phrases in the contents are extracted using text analysis. Each concept is thoroughly examined based on an experts' discussion. Third, *categories* are used to distinguish the hierarchies of concepts. The use of a structured information may significantly increase the number of dimensions and values, thereby making the matrix with a much richer information.

4. Research framework

The article proposes two models for Wikipedia-based approach of morphology building process: basic model and extended model. As shown in Figs. 6 and 7, the basic model is composed of preliminary, dimension development, and value development phase, whereas the extended model takes the identical procedure with an additional subdimension development phase. Basic model is aimed at building morphological matrix in a more concise and intuitive manner, whereas extended model is aimed at building in a more systematic and extensive manner.

4.1. Basic model

The framework of basic model is illustrated in Fig. 6. The model adopts two of the abovementioned features of Wikipedia: *table of contents* and *hyperlinks*. *Table of contents* is used for developing dimensions, and *hyperlinks* and contents are used for developing values.

In preliminary phase, a target subject is selected and a proper name of the target subject is determined based on *redirect links* and *disambiguation pages*. In dimension development phase, *table of contents* is

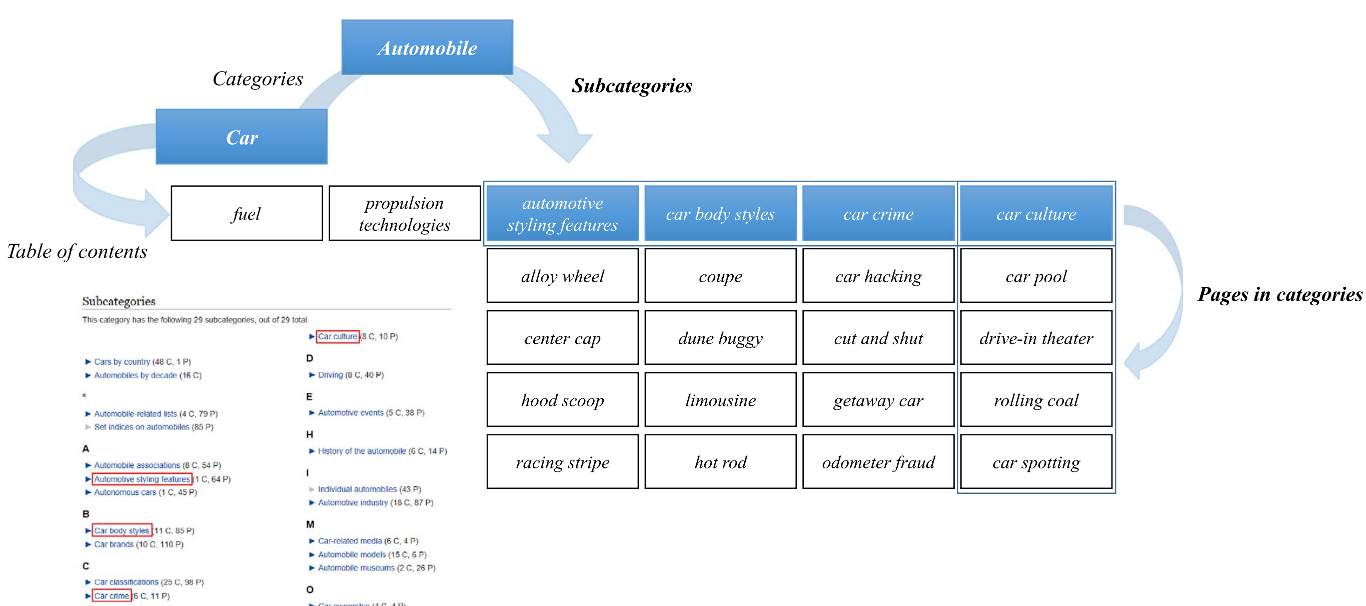


Fig. 5. Example of expanding dimensions and values using *categories*.

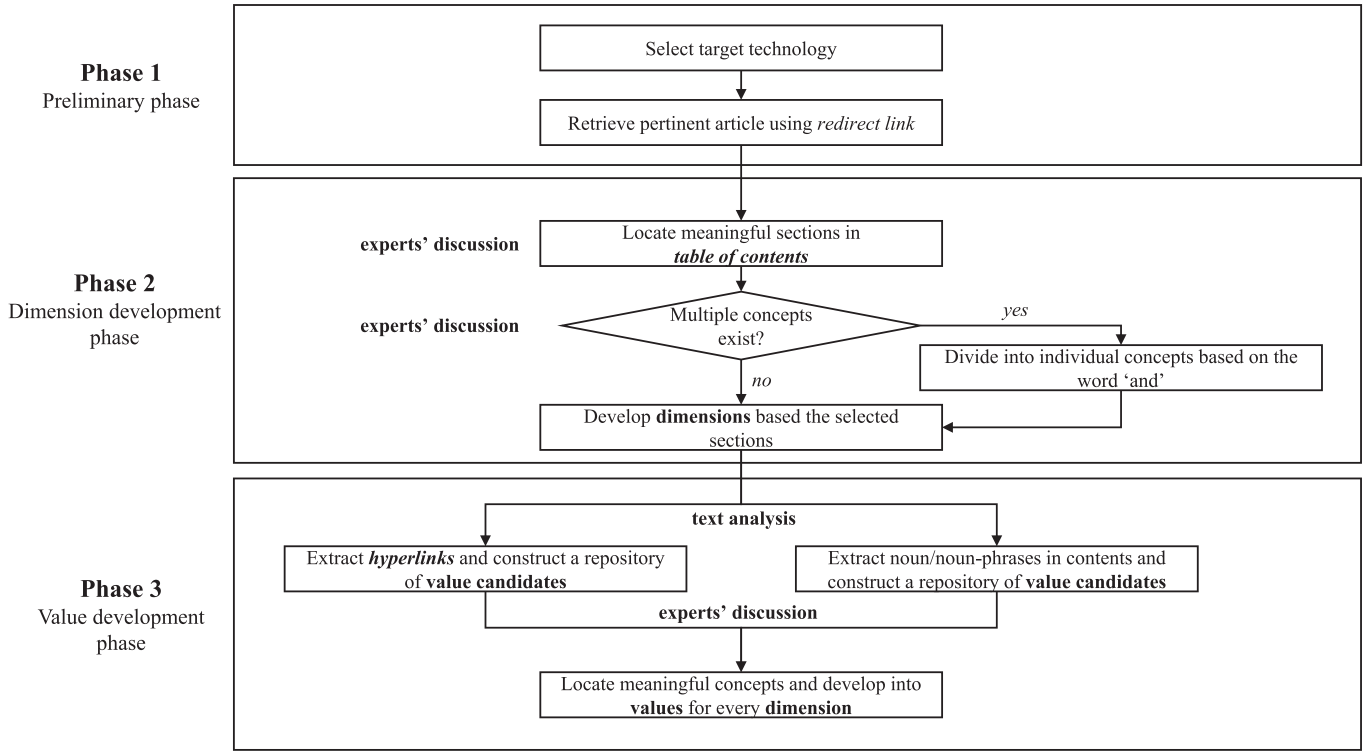


Fig. 6. Overall framework of basic model.

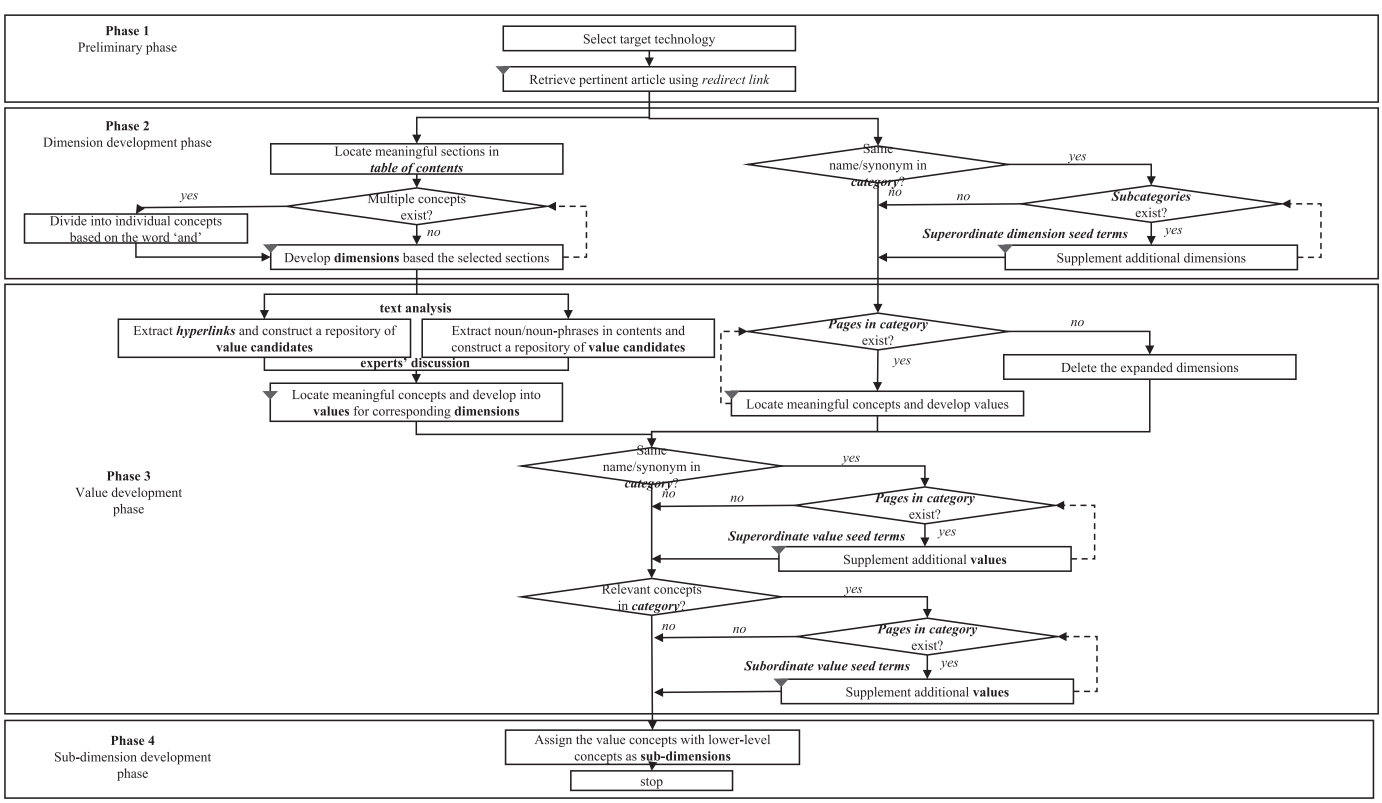


Fig. 7. Overall framework of extended model.

utilized. The overall structure of the target is first investigated through section titles. The sections that contain main composition information are located for dimension development. Due to its inconsistent and incoherent nature, however, a supplementary experts' discussion is required to subjectively select meaningful sections for the investigation. Second, a systematic process of dividing section titles is needed. For the purpose of assigning single concept in each dimension, the sections containing multiple concepts are automatically divided into single concept based on the word "and". The resulting concepts are consequently assigned as dimensions. In value development phase, both *hyperlinks* and contents are used. Text analysis is conducted to extract all *hyperlinks* and nouns/noun phrases of each section, which consequently constitute a repository of value candidates. Once all associated concepts are collected, a thorough discussion is involved to select valuable terms from the repository.

4.2. Extended model

The framework of extended model is illustrated in Fig. 7. As indicated by its name, the model takes dimension and value generation process one step further from basic model by incorporating *categories*. The information of hierarchical structure allows the supplement of superordinate and subordinate concepts, thereby expanding breadth and depth of the morphological matrix. Moreover, the process involves multiple iterative processes (Eriksson and Ritchey, 2002). It is vital to continuously identify and further eliminate inappropriate components for the matrix development. As marked by shaded triangles and dotted arrows in Fig. 7, several in-depth discussions are conducted to repeatedly modify the constituting dimensions and values. To offer a better conceptual understanding of our proposed approach, this subsection describes the process with more details.

4.2.1. Phase 1: preliminary phase

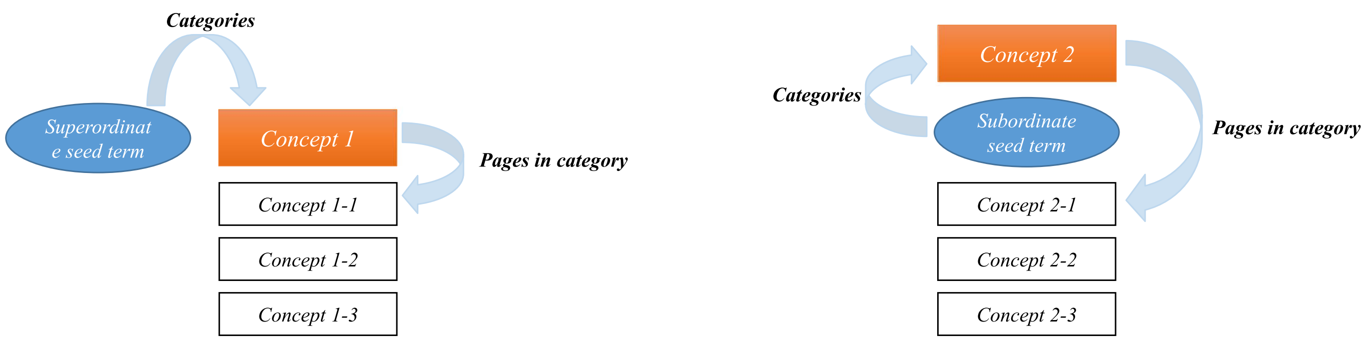
1) *Select a target subject and retrieve pertinent article*
The target subject is first selected. As long as the subject is the main source of an innovation, the selection is highly versatile. It could be a technology, a service, or a company. For instance, emerging technologies are technological products, which are at the brink of commercialization. Because they are highly uncertain and are believed to hold substantial opportunities, emerging technology is a prominent example of an innovation source. This same philosophy could be applied to promising mobile application services or new enterprises. The approach, however, is critically depended on the availability and richness of relevant Wikipedia article. In order to avoid confusion and to maximize data quality, a proper article must be chosen on the basis of the lists provided in *redirect links* and *disambiguation pages*.

4.2.2. Phase 2: dimension development phase

1) *Extract the interested sections*
Depending on the purpose, the composition of the subject will be completely different. For instance, if the interest lies in technological innovation of an emerging technology, the morphological matrix is constructed mainly using technological terms, rather than economic or social terms. To achieve this and for further analysis, we must look into the structure of the article based on *table of contents* and disregard information of history and regulation. Doing so increases the focus of idea generation because we are able to combine information only with that of which we are interested.
2) *Develop basic dimensions of morphological matrix*
Based on the premise that the selected sections represent the main structure of the target subject, each section title is assigned as a dimension of the morphological matrix. An iterative group discussion is required to include only the key sections and to ensure the integration of those dimensions form a coherent whole of the target. Moreover, a systematic process of assigning single concept in each dimension is needed. Some of the sections in *table of contents* comprise multiple concepts due to their contextual relatedness, like fuel and propulsion technologies in the 'car' article. The word 'and' is a great indicator for separating two noun/noun clauses, thus enabling a more automated matrix development.
3) *Locate seed terms and expand dimensions*
This step is aimed at two purposes: increasing the quantity of dimensions and developing a more structured matrix. *Categories*, *subcategories*, and *pages in categories* are accommodated since they yield information regarding the hierarchical relationships of concepts in Wikipedia. This is where seed terms come into play. The word "seed" indicates the concept's capability of reproducing new individual concepts. Each concept in the target subject's *category* list is examined to determine whether there exists a synonym, or whether the subject itself is defined as one of the target's *categories*. The article of 'car', for instance, has a synonym of "automobile", rather than 'car', as shown in Fig. 5. If the target subject is confirmed to hold a *category* structure, numerous lower-level concepts from *subcategories* are extracted and further developed as supplementary dimensions. This is possible since *subcategories* offer various concepts from one step below the target subject, which are at a similar level as dimensions. The chosen concept, like 'automobile', are noted as *superordinate dimension seed terms*, meaning they are superordinate concept capable of providing new subsidiary concepts. In order to supplement the most suitable concepts, a discussion session is repeatedly conducted.

4.2.3. Phase 3: value development phase

1) *Develop basic values of morphological matrix*
The selection of meaningful values is vital in morphological matrix since creative ideas cannot be derived from a small amount of irrelevant and meaningless ingredients. The values, thus, must be assigned with maximized relatedness and diversity. *Hyperlinks* could be served as a great remedy since they hold a wide variety of domain-specific and informative descriptors highly related to dimensions. There exist, however, two major issues when developing values solely based on *hyperlinks*: an inclusion of excessive information and an omission of key information. Due to the inconsistent nature of article structures, they may discard some of the important concepts or, at the same time, contain too much unnecessary details. The 'seating and body style' section, for example, encompasses the contents regarding the types of automobile seats and the types of body styles; however, only the key information concerning body style is expressed in the forms of *hyperlinks*. In response, all nouns/noun phrases within the contents must be extracted using text analysis. Such a process is required to prevent from excluding the essentials. Based on the concepts derived from *hyperlinks* and contents, a repository of value candidates is constructed, and an iterative experts' discussion is further performed to develop meaningful and diverse value concepts in the matrix.
2) *Develop values of expanded dimensions*
The value development is further achieved for the dimensions generated from *subcategories*. *Pages in categories* is particularly used in this step since it is capable of offering all concepts under certain dimension concepts. As in the case of Fig. 5, numerous values, such



(a) Value expansion process using *superordinate seed term*

(b) Value expansion process using *subordinate seed term*

Fig. 8. Value expansion process using seed terms.

as "alloy wheel", "coupe", "car hacking", and "car pool", are generated for the expanded dimensions.

3) *Locate seed terms and expand values*
Similar to the dimension expansion, this step is also aimed at two purposes: increasing the quantity of values and developing a more structured matrix. Value seed terms are identified to expand the number of values based on *categories* and *pages in categories*. These seed terms fall into two groups: *superordinate value seed term* and *subordinate value seed term*, as illustrated in Fig. 8. *Superordinate value seed term* is necessary for expanding values based on high hierarchy value concepts, and *subordinate value seed term* is necessary for expanding based on low hierarchy value concepts. These two seed terms are sequentially utilized to capture both depth and breadth of matrix development.

Among the values derived from the previous step, certain value concepts that are capable of supplementing new subsidiary concepts are first identified. In details, each value concept is examined whether the concept itself is defined as one of the concept's *categories*. This is achieved through tracing same category name or synonyms in the *category* list of the concept, as shown in Figs. 4(a) and 8(a). The use of *redirect pages* and *disambiguation page* is vital when dealing with the concepts derived from the contents because a new proper article must be first defined in order to obtain the right *categories* list. Once these value concepts are confirmed to hold a *category* structure, numerous lower-level concepts under the value concepts are extracted from *pages in categories* and further developed as supplementary values of the morphological matrix. This process is identical to that of dimension expansion. An iterative experts' discussion is also necessary to exclude the irrelevant concepts. The chosen value concepts that successfully meet these conditions are noted as *superordinate value seed terms*, meaning they are superordinate concept capable of providing new subsidiary concepts.

However, the sole use of *superordinate seed terms* cannot quite cover all associated concepts since some values themselves are too low in the hierarchy. *Subordinate seed terms* are used to cope with such an issue. Certain value concepts are considered subordinate terms serving to locate alternative superordinate concepts, capable of providing additional low-level concepts. As shown in Figs. 4(b) and 8(b), the most suitable higher-level concept is first identified from the list of *categories* of the value concept. The use of *redirect links*, *disambiguation page*, and an iterative experts' discussion are vital for the concept selection. After confirming the availability of *pages in categories*, numerous lower-level concepts are extracted and further developed as the values of the morphological matrix. Such a value expansion process allows the retrieval of disparate information sources. By way of illustration, when the contents of 'seating and body style' section is text analyzed, the concept "seat" is extracted from the contents. Then, the concept of "auto parts" can be used as the value seed term, which is selected from the *categories* of "car seat" article, to generate value concepts. As a result, the concepts of "bench seat", "bucket seat", "jump seat", "rumble seat" and "third row seating" can be extracted from "*pages in categories*". The intermediary concepts, like 'seat', are noted as *subordinate value seed terms*, meaning they are subsidiary concept capable of providing a key superordinate concept, like 'auto parts'.

4.2.4. Phase 4: sub-dimension development

1) *Develop sub-dimensions*
The structure of the matrix has been significantly extended from the value expansion process. Nonetheless, not only each dimension holds an excessive number of value concepts but multiple sub-hierarchies often exist in a single dimension. This is primarily caused by hierarchical gap between dimensions and values. In response, an intermediary concept of sub-dimension is introduced to bridge such a gap and adjust the matrix structure. All concepts that are capable of providing low-level concepts, specifically superordinate seed terms and the concepts derived from subordinate seed terms, are assigned as sub-dimensions. These concepts are presented with orange boxes in Figs. 4 and 8.

5. Illustrative case study: drone technology

The process of our proposed methodology is demonstrated with an illustrative case study of an emerging technology-UAV, or so-called drone technology. As stated earlier, emerging technology is a perfect example for performing a creative idea generation process since it holds high level of both uncertainty and opportunity (Kwon et al., 2016). By coherently structuring and creatively recombining the components, new forms of technologies with novel functions or different application uses could possibly be derived. Drone technology, in particular, is considered a new wave of technology giant. It enables a whole new level of innovation by altering the existing business landscape, including delivery and recreation industries. In this section, Wikipedia article of drone technology is investigated, and a morphological matrix is systematically constructed on the basis of associated information. The case study is conducted in a consecutive manner: the development of basic model continued by that of extended model.

Table 4
Illustration of morphological matrix (basic model).

Power supply	Platform	Computing	Sensors	Actuators	Communications	Autonomy
Lithium polymer batteries	Battery elimination circuitry	System on a chip	Exteroceptive sensors	Actuators	Radio frequency front-end	Hierarchical control systems
	Microcontroller unit	Single board computers	Non-cooperative sensors	Digital electronic speed controllers	Antenna	Scripting language
		Flight controller	Collision avoidance	Engines	Analog-to-digital converter	Finite-state machine
		Flight controller board	Gyroscopes	Propellers	Data link	Behavior trees
			Accelerometers	Servomotors	Telemetry	Hierarchical task planners
			Inertial measurement unit	Weapons	Satellite navigation	PID controller
			Compass	Payload actuators	Radio transmitter	Motion planning
			Barometer	LEDs	Ground control station	Tree searches
			GPS receiver	Speakers	Wearable devices	Genetic algorithms
					Electroencephalography	Self-level
					Uplink	Altitude hold
					Downlink	Hover hold
					Real-time video	Headless mode
					Downstream	Care-free
					Smartphone	Take-off
					Tablet	Autoland
					Computer	Aerobatics
					Human movement recognition	Camera

5.1. Basic model

Drone technology is selected for the target subject. The analysis begins with retrieving the article of interest from Wikipedia website. The "drone" article regarding robotic vehicle of "unmanned aerial vehicle" is identified and retrieved from its *redirect page*. Then, dimension development phase is conducted using *table of contents*. Every section and sub-section of *table of contents* is thoroughly investigated and selected for dimension development of morphological matrix. In this particular case study, technical configuration of drone technology was of interest since such an ill-defined technology is in its embryonic stage with unclear technological standards and specifications. The sub-sections of "body", "power supply and platform", "computing", "sensors", "actuators", "software", "loop principles", "flight controls", and "communications" and the sections of "autonomy" and "functions" contained structured and fruitful technical information. They were considered as our basic dimensions of morphological matrix. Based on the term 'and', the dimension of 'power supply and platform' is separated into two individual dimensions: "power supply" and "platform". The next was value development phase. Basic model generated values using the concepts extracted from *hyperlinks* and contents. Text analysis was carried out to extract the noun/noun phrases in the contents. A group discussion was further conducted to select the meaningful concepts from the repository. The group comprised three experts having experience in technology forecasting and management from four years to five years and two experts having experience in mechatronics from three years to four years. A representative result of the morphological matrix is shown in Table 4. The full result is presented in Appendix A, where *hyperlinks* are noted in blue and nouns/noun phrases extracted from the contents are noted in black.

5.2. Extended model

The following model is extended from the result of the basic model. Based on the premise that the matrix is constructed as shown in Fig. 4, the first part of Extended model is identifying *superordinate dimension seed terms* and expanding the number of dimensions by supplementing subsidiary values. The concept of 'unmanned aerial vehicle' was located in the *categories* list of the article, and it was further identified that the article included several *subcategories* concepts. Among the many, only "unmanned aerial vehicle manufacturers" was considered meaningful and adequate enough to become the supplementary dimension. As conducted in the basic model, experts' discussions were involved throughout the analysis.

The second part is expanding the number of values. The values of the expanded dimensions are first derived based on *pages in categories*. In this particular case example, the concepts were derived only from the dimension of 'unmanned aerial vehicle manufacturers', as shown in the far right column of Table 6. *Superordinate value seed terms* are then involved to expand the values based on high-hierarchy concepts. Each existing value concept was examined whether it be capable of supplementing lower-level concepts. The modified matrix on the basis of *superordinate value seed terms* is partially illustrated in Table 6 and fully presented in Appendix B. Given the space constraints, only four or five

Table 5
List of seed terms (*hyperlinks*) of drone technology.

Superordinate dimension seed terms	Unmanned aerial vehicle manufacturers
Superordinate value seed terms	Lithium polymer batteries, microcontroller unit, system on a chip, single board computers, gyroscopes, accelerometers, actuators, propellers, LEDs, aircraft controls, air brake, antenna, telemetry, electroencephalography, scripting language, finite-state machine, tree searches, genetic algorithms
Subordinate value seed terms	Lithium polymer batteries, microcontroller unit, compass, GPS receiver, digital electronic speed, controllers, LEDs, open loop, closed loop, plane flight dynamics, analog-to-digital converter, data link, satellite navigation, radio transmitter, hierarchical task planners, motion planning

Table 6
Illustration of modified morphological matrix using superordinate seed values (extended model).

Power supply	Sensors	Actuators	Communications	Autonomy	Manufacturers
Lithium polymer batteries	Exteroceptive sensors	Actuators	Radio frequency front-end	Hierarchical control systems	3D Robotics
	Non-cooperative sensors	Helical band actuator	Antenna	Scripting language	AeroDreams
	Collision avoidance	Linear actuator	Loop antenna	ActivePerl	DJI
	Gyroscopes	Plasma actuator	Antenna boresight	AMPL	Flirtey
	Anti-rolling gyro	Rigid chain actuator	Batwing antenna	HyperTalk	Sky-Watch
	Control moment gyroscope	etc.	Array gain	Rexx	
	Fibre optic gyroscope	Digital electronic speed controllers	Dipole antenna	etc.	
	Quantum gyroscope	Engines	Halo antenna	Finite-state machine	
	etc.	Propellers	Spiral antenna	Alternating finite automation	
	Accelerometers	Modular propeller	Ec.	Asymmetric numeral systems	
	Gravimeter	Scimitar propeller	Analog-to-digital converter	Buchi automation	
	Laser accelerometer	Cyclorotor	Data link	Quotient automaton	
	Liquid capacitive inclinometers	Contra-rotating propellers	Telemetry	etc.	
	PIGA accelerometer	etc.	EMR telemetry	Behavior trees	
	etc.	Servomotors	Electronic data capture	Hierarchical task planners	
	Inertial measurement unit	Weapons	Remote data capture	PID controller	
	Compass	Payload actuators	Remote terminal unit	Motion planning	
	Barometer	LEDs	Wildlife radio telemetry	Tree searches	
	GPS receiver	LED circuit	etc.	and-or tree	
		LED lamp	Satellite navigation	k-ary tree	
		LED strip light	Radio transmitter	Suffix tree	
		etc.	Ground control station	Radix tree	
		Speakers	Wearable devices	Trace tree	
			Electroencephalography	etc.	
			Beta wave	Genetic algorithms	
			Spike-and-wave	Cultural algorithm	
			PGO waves	Fitness function	
			Evoked potential	Genetic fuzzy systems	
			Ear-EEG	Genetic programming	
			Etc.	etc.	
			Uplink	Self-level	
			Downlink	Altitude hold	
			Real-time video	Hover hold	
			Downstream	Headless mode	
			Smartphone	Care-free	
			Tablet	Take-off	
			Computer	Autoland	
			Human movement recognition	Aerobatics	
				Camera	
				Digital camera	
				Remote camera	
				Still camera	
				Video camera	
				etc.	

additional values were included in the result, and the rest were noted as "etc.". The supplemented values from *superordinate value seed terms* are noted in orange in Appendix B.

This morphological matrix is constructed by generating additional values from the result of basic model. The resulting *superordinate value seed terms* are listed in Table 5. By way of illustration, the value concepts of "accelerometers" and "propellers" from 'sensors' and 'actuators' dimensions satisfy two conditions. They are the concepts that have same *category* names in the *categories* list and have numerous subsidiary concepts within *pages in categories*. These two seed terms resulted the augmentation of multiple concepts, including "gravimeter", "laser accelerometer", "liquid capacitive inclinometer", "modular propeller", "scimitar propeller", "cyclorotor", and "contra-rotating propellers".

The last part of value expansion involves the use of *subordinate value seed terms*. Each existing value concept was examined to determine whether it is capable of detecting a higher-level concept, which could supply additional subsidiaries. This step is useful for expanding values based on relatively low-hierarchy concepts. The modified matrix using *subordinate value seed terms* is partially illustrated in Table 7 and fully presented in Appendix C. Given the space constraints, only four or five additional values were included in the result. The supplemented values from *subordinate value seed terms* are noted in red in Appendix C. The resulting *subordinate value seed terms* are also listed in Table 5.

To illustrate, the value concept of "radio transmitter" in 'communications' dimension is quite low in hierarchy to have subsidiary concepts; however, it may be included in a meaningful high-level concept like "telecommunication equipment", which could further provide multiple subsidiary concepts, including "block upconverter", "hybrid coil", "radio spectrum scope", and "optical line termination". A higher-level concept is located in the categories list of 'radio transmitter', and the subsidiary concepts are extracted from the *pages in categories* of that higher-level concept. However, there are some instances where a certain value concept could become both *superordinate* and *subordinate value seed terms*. The value concept of "LEDs", for instance, may provide

Table 7
Illustration of modified morphological matrix using subordinate seed values (extended model).

Power supply	Sensors	Actuators	Communications	Autonomy	Manufacturers
Lithium ion batteries	Exteroceptive sensors	Engines	Radio electronics	Hierarchical control systems	3D Robotics
Lithium polymer batteries	Non-cooperative sensors	Servomotors	Radio frequency front-end	Scripting language	AeroDreams
Solid-state lithium-ion battery	Automotive safety technologies	Weapons	RF power margin	ActivePerl	DJI
18650 battery	Collision avoidance	Payload actuators	Image response	AMPL	Flirtey
Dual carbon battery	Drive by wire	Speakers	Feed line	AngelScript	Sky-Watch
Graphene foam	Child safety lock	Actuators	RF probe	HyperTalk	
Lithium hybrid organic battery	Shock absorber	Helical band actuator	Transceiver	Rc	
Lithium ion manganese oxide battery	Crosswind stabilization	Linear actuator	Radio frequency front-end	Rexx	
Lithium iron phosphate battery	Gyroscopes	Plasma actuator	Antenna	Finite-state machine	
Lithium-air battery	Anti-rolling gyro	Rigid chain actuator	Loop antenna	Alternating finite automation	
Lithium-sulfur battery	Control moment gyroscope	Propellers	Antenna boresight	Asymmetric numeral systems	
Lithium-titanate battery	Fibre optic gyroscope	Modular propeller	Batwing antenna	Buchi automation	
Lithium-ion flow battery	Quantum gyroscope	Scimitar propeller	Array gain	Krohn-Rhodes theory	
Nanoball batteries	Accelerometers	Cyclorotor	Dipole antenna	Quotient automaton	
	Gravimeter	Contra-rotating propellers	Halo antenna	Permutation automation	
	Laser accelerometer	Power electronics	Spiral antenna	Behavior trees	
	Liquid capacitive inclinometers	Digital electronic speed controllers	Digital signal processing	Automated planning and scheduling	
	PIGA accelerometer	Commutation cell	Analog-to-digital converter	Hierarchical task planners	
	Inertial measurement unit	Gate driver	Aliasing	State space planning	
	Navigational equipment	Magnetic amplifier	Bandlimiting	Partial-order planning	
	Compass	Power module	Infinite impulse response	Kinodynamic planning	
	Inertial navigation system	Power semiconductor device	Oversampling	Multi-agent planning	
	Pressure reference system	Optic diodes	Half-band filter	Reactive planning	
	Ecompass	LEDs	Data transmission	PID controller	
	Transfer alignment	LED circuit	Data link	Robot kinematics	
	Barometer	LED lamp	Adaptive equalizer	Motion planning	
	Global positioning system	LED strip light	Backward channel	Kinodynamic planning	
	GPS receiver	Crystal LED	Bandwidth cap	Kinematic chain	
	Clock drift	Flexible OLED	Narrative traffic	Articulated robot	
	Digital anchor	Phosphorescent OLED	Parity bit	Passive dynamics	
	Vehicle tracking system	Superluminescent diode	Telemetry	Serial manipulator	
	Positioning system		EMR telemetry	Tree searches	
	Pseudorange		Electronic data capture	and-or tree	
			Remote data capture	k-ary tree	
			Remote terminal unit	Suffix tree	
			Wildlife radio telemetry	Radix tree	
			Satellite navigation system	Trace tree	
			Satellite navigation	Genetic algorithms	
			Timation	Cultural algorithm	
			Total electron content	Fitness function	
			Vehicle tracking system	Genetic fuzzy systems	
			Hybrid positioning system	Genetic programming	
			Automatic vehicle location	Truncation selection	
			Telecommunication equipment	Self-level	
			Radio transmitter	Altitude hold	
			Block upconverter	Hover hold	
			Hybrid coil	Headless mode	
			Radio spectrum scope	Care-free	
			Network termination	Take-off	
			Optical line termination	Autoland	
			Ground control station	Aerobatics	
			Wearable devices	Optical devices	
			Electroencephalography	Camera	
			Beta wave	Digital camera	
			Spike-and-wave	Remote camera	
			PGO waves	Still camera	
			Evoked potential	Video camera	
			Ear-EEG	Range imaging	
			Uplink	Wright camera	
			Downlink	Night vision devices	
			Real-time video	Laser beam profiler	
			Downstream	Head-up display	
			Smartphone	Electric eye	
			Tablet		
			Computer		
			Human movement recognition		

Table 8
Illustration of modified morphological matrix using sub-dimensions (extended model).

Communications							
Telecommunication equipment	Satellite navigation system	Data transmission	Digital signal processing	Electroencephalography	Telemetry	Antenna	Radio communications stubs
Radio transmitter	Satellite navigation	Data link	Analog-to-digital converter	Beta wave	EMR telemetry	Loop antenna	Radio frequency front-end
Block upconverter	Timation	Adaptive equalizer	Aliasing	Spike-and-wave	Electronic data capture	Antenna boresight	RF power margin
Hybrid coil	Total electron content	Backward channel	Bandlimiting	PGO waves	Remote data capture	Batwing antenna	Recurrent rotation
Radio spectrum scope	Vehicle tracking system	Bandwidth cap	Infinite impulse response	Evoked potential	Remote terminal unit	Array gain	Thermal fade
Network termination	Hybrid positioning system	Narrative traffic	Oversampling	Ear-EEG	Wildlife radio telemetry	Dipole antenna	Spurious emission
Optical line termination	Automatic vehicle location	Parity bit	Half-band filter			Halo antenna	M-ray transmission
						Spiral antenna	

numerous subsidiary concepts, like “LED circuit”, “LED lamp” and “LED strip light”; at the same time, it may yield the higher-level concept of “optic diodes” to supplement the concepts of “crystal LED”, “flexible OLED”, and “phosphorescent OLED”.

Finally, sub-dimensions are developed to prevent hierarchical value concepts from existing in a single dimension. All concepts expanded from the value seed terms may be involved with such an issue, including *superordinate value seed terms* and the higher level concept derived from *subordinate value seed terms*. For instance, ‘accelerometers’ and ‘propellers’ are assigned as sub-dimensions of ‘sensors’ and ‘actuators’, in respective. Moreover, ‘telecommunication equipment’ is developed into a sub-dimension, and the *subordinate value seed term* of ‘radio transmitter’ is assigned as one of the comprising values. All concepts that are capable of providing low-level concepts are assigned as sub-dimensions. The modified matrix of using *sub-dimensions* is partially illustrated with ‘communications’ dimension, as shown in Table 8. The full result is presented in Appendix D.

6. Comparative analysis

6.1. Experimental setup

The feasibility of the proposed methodology was verified via illustrative case study; however, its effectiveness and internal validity have not yet been fully shown. In response, we have conducted a comparative analysis between the proposed approach and the existing classical approach. A new morphological matrix solely depending on a focus group discussion was conducted on the target subject of drone technology. The focus group was composed of three experts having a minimum of four years of experience in technology forecasting and management and two experts having a minimum of three years of experience in mechatronics. We have followed an interactive-based nominal group discussion process since a group interactive discussion was prone to several human biases and dysfunctional behaviors (Sutton and Arnold, 2013). The process involved three sessions: (1) introduction session, (2) individual brainstorming session, and (3) interactive discussion session.

The discussion was led by a moderator. First, a short introduction session was conducted to provide the background and objective of this research and to demonstrate general overview of morphological analysis. The specifics regarding the technique were prepared and presented by the experts in technology forecasting and management. Second, the participants were asked to individually brainstorm and generate a list of technical components that could be included in the parts of drone technology. The list was constructed for both dimensions and values. Finally, the moderator collected the list generated from each participant and further constructed an aggregated list to initiate an interactive discussion. The participants gave questions or comments of each component in order to develop a complete set of dimensions and values that all members can agree upon. In result, major frames of UAV, such as “controller”, “frames”, and “motors”, were assigned as dimensions as presented in Table 9.

6.2. Comparison of results

In terms of dimension development, the morphological matrix derived from the discussion-based approach was composed of 12 dimensions. They were the most representative and general concepts that fundamentally comprise the primary structure of a drone technology. When compared with the dimensions of Wikipedia-based approach, the proposed approach not only successfully covered every dimension of the discussion-based method but offered more specific and comprehensive concepts, as shown in Table 10. To illustrate, while the classical

Table 9
Illustration of morphological matrix using discussion-based approach.

Dimensions	Controllers	Frames	Motors	Propellers	Batteries	Safety systems	Landing gears	Electronics speed controllers	GPS modules	Antenna	Camera	Sensors	Communications
Values	AVR	Tricopter	Brushed	Standard	Lithium polymer (LiPo)	Battery monitor	Fixed landing gears	DYS	Glonass - latest one	Loose wire whip	Front-facing	Thermal sensor	Radio control (RC)
	PIC	Quadcopter	Brushless	Pusher	Lithium	Parachute	Retractable landing gears	Diatone	Unmanned Tech	Helical “rubber ducky”	Down-facing	Sonar ranging	Bluetooth
	ARM	Hexacopter	Coreless	Plastic	Lithium sulfide (LiSTM)	GPS tracking	Speading wings s1000+	Eachine	Emlid	Circularly polarized cloverleaf antenna	3D camera	Accelerometer	WiFi
	Pixhawk	Y6	Servo	Carbon fibre	CoreTexRC	Black box	Inspire 1	Emax	Hex Technology	Linear polarized antenna	CMOS camera	Gyroscope	Radio frequency
	The Flip32+	Octocopter	Electric	Gemfan	DJI	Low battery alarm	Voyager 3	Sunrise model		Circular polarized antenna	CCD camera	Inertia measurement unit (IMU)	
		×8	AltiGator	Hqprop	Fatshark		Scout ×4	Unmanned Tech		Directional antenna	Depending on latency	Compass/magnetometer	
			T-Motor	APC	Gens Ace		QR X900	DJI Inspire 1		Omnidirectional antenna	Resolution	Pressure/barometer	
			Axi	Luminier	SkyRC					Duck	Dynamic range	Infrared	
			Roxxy	3-Blade	Unmanned Tech					Skew planar	IR sensitive camera		
			Dualsky	2-Blade	Yuneec					Cloverleaf	IR blocked camera		
										Array	Night camera		
										Helical			
										Patch			
										Crosshair			
										Yagi			

Table 10
Comparison of dimensions between discussion-based approach and Wikipedia-based approach.

Discussion-based approach	Wikipedia-based approach	
Dimension	Sub-dimensions	Dimensions
Controllers	Embedded systems, microtechnology	Platform, computing
Frames	Rotorcraft	Body
Motors	Actuators	Actuators
Propellers	Propellers	Actuators
Batteries	Lithium ion batteries	Power supply
Safety systems	Automotive safety technologies	Sensors
Landing gears	Aircraft landing systems	Autonomy
Electronics speed controllers (esc)	Power electronics	Actuators
GPS modules	Global positioning system	Sensors
Antenna	Antenna	Communications
Camera	Optical devices	Autonomy
Sensors	Automotive safety technologies, gyroscopes, accelerometers, navigational equipment, global positioning system	Sensors
Communications	Telecommunication equipment, satellite navigation system, data transmission, digital signal processing, electroencephalography, telemetry, antenna, radio communications stubs	Communications

approach generated a single dimension of 'communications', the Wikipedia-based approach offered more specific component-related dimensions, including 'telecommunication equipment', "digital signal processing", "satellite navigation system", "data transmission", "electroencephalography", "telemetry", etc. Moreover, Wikipedia-based methodology offered wider ranging concepts, such as 'optic diodes', 'software', 'loop principles', 'flight controls', "robot kinematics", "scripting language", and so on. The generation of both dimensions and sub-dimensions is expected to increase the number of specified and extensive range of concepts.

In terms of value development, the overall value structure of discussion-based approach was simple and concise. Compared to the result of Wikipedia-based approach, the method offered more domain-specific and generalized value information. For example, discussion-based method provided the value concepts regarding widely-accepted types, compositions, and brands of drone 'propellers'. There were "standard", "pusher", "3-blade", or "2-blade" types of propellers, which are generally composed of either "plastic" or "carbon fibre". Such a domain-specific input data is capable of generating relatively reliable ideas without much of noise. Nonetheless, it was difficult to expect any unanticipated and novel results since the input itself was composed of known and obvious information.

The effect of Wikipedia is quite different from that of the discussion-based approach. The most noticeable advantage was that the number of values were considerably greater, compared to that of the conventional method. Furthermore, the major strengths of using Wikipedia data were of two kinds: (1) diversity and (2) specificity. In terms of diversity, the proposed approach offered innovation-related and interdisciplinary information, while ensuring generalized and widely-used information. For instance, we have identified that "lithium polymer batteries" is a *subordinate value seed term*, which could derive a higher-level concept of "lithium ion batteries". Even though lithium polymer battery (Li-Po) is a common battery type of drone technology, there were numerous other variations of the lithium-ion batteries could potentially be applied in drone technology. Based on the seed term of 'lithium ion batteries', several meaningful value concepts of "nanowire battery", "thin film lithium-ion battery", and "graphene foam" were identified. 'Nanowire battery' is not commercially available; however, they are considered one of the promising technologies hoping to replace traditional graphite anode. 'Thin film lithium-ion battery' and 'graphene foam' can be applied to nano- or micro-drones based on its small size and flexible nature. Moreover, the use of 'electroencephalography', which was noted as "human brain waves" in the article, is an unconventional way of communicating and further controlling hobby drones. When such unprecedented and novel concepts are included, much diverse and innovative ideas will result from a reconfiguration process.

Furthermore, the approach occasionally generated the information from pertinent but different domain. For example, the sub-dimension of "automotive safety technologies" was extracted based on *subordinate value seed term* of "collision avoidance". Despite its general use in field of autonomous cars, the value concepts like "shock absorber", "drive by wire", and "child safety lock" could be effectively used and further integrated in drone technology. Other value concepts include "aerodynamics" and "aircraft landing systems" from avionics; "finite-state machine", 'robot kinematics', and 'digital signal processing' from electronics and robotics; and "fibre optic gyroscope" and "ring laser gyroscope" from satellite missile industry. Such an off-domain information may spark creativity by providing solutions from disparate disciplines, thereby stimulating a more interdisciplinary development of a drone technology.

In terms of specificity, the proposed approach not only provided more product-related information but also offered specific component- or logic- related information of corresponding dimensions. By way of illustration, the dimension of 'controller' in discussion-based approach is composed of very rudimentary product-related values, such as "AVR", "PIC", "ARM", "Pixhawk", etc. These value concepts were the most commonly used microcontrollers when building drones. However, the sub-dimensions of "embedded systems" and "microtechnology", which were developed on the basis of seed values in the proposed methodology, generated an innumerable number of controlling products while covering each and every value concept in discussion-based approach. The values of "AVR2" and "Arduino" from Wikipedia-based method corresponded to 'AVR' from discussion-based method; "PIC microcontroller" corresponded to 'PIC'; "STM8" and "STM32" corresponded to 'ARM', 'Pixhawk' corresponded to "PX4 autopilot". Additionally, the proposed approach further produced more specified value concepts: language-related information of "embedded c", "embedded java", "Ada", "Lua", "BasicX", etc.; system-related information of "slugs", "low-voltage detect", "priority inversion", etc.; component-related information of "oscillator start-up timer", "sensor node", "interdigital transducer", etc. Such an increase of values concepts may help technology designers to think outside the box. For example, the values of "remote terminal unit" and "wildlife radio telemetry" in the sub-dimension of 'telemetry' may suggest novel application areas, such as wildlife monitoring, mine sites, or swimming pool control.

7. Intrinsic limitations of applying Wikipedia

Along with aforementioned benefits, our findings in this article are subject to at least three intrinsic limitations. The most critical shortfall lies in the fact that the process is highly dependent on the availability and richness of relevant Wikipedia articles. The cells of the morphological matrix are developed based on the contents existing in the selected page. However, the articles regarding new and emerging issues may hold a very small amount of, or even no, information; whereas the ones regarding matured and established issues may hold an excessive amount of information. For example, the article of 'car' hold an abundance of contents; whereas the article of "e-textiles" hold insufficient amount of information to even develop the dimensions. The inclusion of a proper amount of information is vital. To cope with such an issue, the right model must be selected depending on the quality of the article: basic model for a matured subject and extended model for an emerging subject. Moreover, if the article contains only little content, the process can rely only on the development of value development and sub-dimension development. Since the derived sub-dimensions could substitute the role of dimensions, the extended model could skip dimension development and dimension expansion parts and start with text analyzing *hyperlinks* and contents. If the article is missing, other substitutable subject matter must be thoroughly sought.

Second, we have highlighted the importance of an expanded knowledge pool of Wikipedia data and its role in making the matrix more fruitful; however, this could be pointed out as the limitation of using Wikipedia. Because the contents of Wikipedia are edited by everyone-not just experts but also anonymous novices-the reliability and accuracy of a crowd-sourced knowledge source can be questioned (Lavsa et al., 2011). Moreover, the problem regarding context inconsistency must be highlighted. Self-looping problems, for instance, exist given the random usage of *hyperlinks*, and no standardized structures of *table of contents* exist in Wikipedia. Such issues may result the omission of valuable information and the inclusion of unnecessary information in dimension and value development processes. To deal with, we have conducted a text analysis to extract noun/noun phrases directly from the contents and have incorporated focus group discussion sessions. Yet, a more systematic and sophisticated procedure is necessary for a general use of the proposed approach. For instance, the information within the contents and *table of contents* should be exploited more effectively when expanding the dimensions and values.

Finally, the proposed approach cannot fully replace human intervention. Every step from generating dimensions to expanding values requires expert judgments, as illustrated in Fig. 7. To better reconcile different opinions and refine the structure of morphological matrix, other existing idea generation techniques dealing with extracting knowledge from experts, including Delphi (Dalkey, 1969), brainstorming (Osborn, 1957), or brainwriting (VanGundy, 1981), must be incorporated. These structured methodologies are useful in supporting decision making process and enhance group creativity. An integration with a web-based software could also be useful in promoting shared understanding among experts and stakeholders (Zec et al., 2015; Zec and Matthes, 2017). In addition, a more sophisticated text mining techniques could be integrated to minimize human involvement. Such an incorporation could be particularly useful in combining the values and generating ideas, which are the most challenging steps of morphological analysis. The proposed approach accommodated only the basic techniques of text analysis: part-of-speech tagging and extraction of terms. However, if the concepts' semantic relationships are identified based on their co-occurrence measures, relatively logical and reasonable combinations could be derived. Furthermore, a visualization-based idea generation process will be possible on the basis of these measures, which could better stimulate communication between the participants and support decision-making process (Veryzer and Borja de Mozota, 2005).

8. Concluding remarks

Morphological analysis is deemed appropriate and necessary to generate new creative ideas given its objective, impersonal, and systematic nature. Conventionally, the process was only conducted by a handful number of experts and stakeholders. The participants had to be assembled in a certain place and be instructed to subjectively decompose a target matter into multiple components. Despite its many advantages, the approach was conducted with the input source subject to a limited spectrum of biased knowledge bases. Furthermore, such a knowledge pool seems quite unsuitable considering a highly complex and uncertain nature of today's matters. This research, in response, proposes a Wikipedia-based approach to the development of morphological matrix, which could be served as a supporting and supplementary tool for generating creative ideas. The fundamental premise is that creative ideas are crafted from a novel combination of existing but previously separated ideas. Wikipedia data source was incorporated considering its case-specific information and well-coordinated knowledge structure. Two models are presented: basic model and extended model. Basic model was aimed at constructing the morphological matrix in a more concise and intuitive manner; whereas extended model was aimed at constructing in a more systematic and extensive manner.

As a result, the proposed approach generated more specified and diversified morphological matrix, and three major intrinsic features of Wikipedia have been identified as major contributing factors: extended knowledge pool, case-specific knowledge content, and well-coordinated knowledge structure. First, Wikipedia platform enabled individuals from different background and expertise to participate in defining and structuring concepts. It has obtained and further converged a variety of perspectives to minimize subjectivity. Second, Wikipedia offered an abundance of case-specific knowledge that could better stimulate specialized and practical idea generation. Finally, Wikipedia had a well-coordinated knowledge structure that enabled the systematic decomposition of a certain target. In details, *table of contents* allowed overviewing the structure of certain subject; *hyperlinks* allowed extracting the most useful and relevant information; and *categories* allowed understanding complex hierarchical structure of the concepts. However, the current study still cannot replace classical expert rounds in creative idea generation. The proposed approach is rather a preliminary or exploratory attempt to apply other valuable knowledge sources in morphological analysis, thereby increasing the possibility of generating more innovative and novel ideas. If the debate is to be moved forward, further experimental investigations regarding more systematic and effective procedures of knowledge extraction and creative component combination are needed.

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Appendix A. The result of Wikipedia-based morphological matrix (basic model)

Dimensions	Body	Power supply	Platform	Computing	Sensors	Actuators	Software	Loop principles	Flight controls	Communications	Autonomy
Values	Tailless quadcopter	Lithium polymer batteries	Battery elimination circuitry	System on a chip	Exteroceptive sensors	Actuators	Real-time	Open loop	Plane flight dynamics	Radio frequency front-end	Hierarchical control systems
	Rotary wing		Microcontroller unit	Single board computers	Non-cooperative sensors	Digital electronic speed controllers	Raspberry Pis	Closed loop	Aircraft controls	Antenna	Scripting language
	Mono-			Flight controller	Collision avoidance	Engines	Beagleboards	Hybrid control	Air brake	Analog-to-digital converter	Finite-state machine
	Bi-			Flight controller board	Gyroscopes	Propellers	NavIO	Positive	Autopilot	Data link	Behavior trees
					Accelerometers	Servomotors	PXFMini	Faster	Helicopter flight dynamics	Telemetry	Hierarchical task planners
					Inertial measurement unit	Weapons	Nuttx	Slower	Multirotor flight dynamics	Satellite navigation	PID controller
					Compass	Payload actuators	Xenomai	Left		Radio transmitter	Motion planning
					Barometer	LEDs	DDS-ROS 2.0	Up		Ground control station	Tree searches
					GPS receiver	Speakers	KKMultiCopter	Down		Wearable devices	Genetic algorithms
							ArduCopter	Feedback		Electroencephalography	Self-level
								Tailwind		Uplink	Altitude hold
								Feed forward		Downlink	Hover hold
										Real-time video	Headless mode
										Downstream	Care-free
										Smartphone	Take-off
										Tablet	Autoland
										Computer	Aerobatics
										Human movement recognition	Camera

Appendix B. The result of Wikipedia-based morphological matrix after applying *superordinate value seed terms* (extended model)

Dimensions	Body	Power supply	Platform	Computing	Sensors	Actuators	Software	Loop principles	Flight controls	Communications	Autonomy	Manufacturers
Values	Tailless quadcopter	Lithium polymer batteries	Battery elimination circuitry	System on a chip	Exteroceptive sensors	Actuators	Real-time	Open loop	Plane flight dynamics	Radio frequency front-end	Hierarchical control systems	3D Robotics
	Rotary wing		Microcontroller unit	Advanced microcontoller bus architecture	Non-cooperative sensors	Helical band actuator	Raspberry Pis	Closed loop	Aircraft controls	Antenna	Scripting language	AeroDreams
	Mono-		Embedded controller	MPSoC	Collision avoidance	Linear actuator	Beagleboards	Hybrid control	Airbrake	Loop antenna	ActivePerl	DJI
	Bi-		Arduino	Amlogic	Gyroscopes	Plasma actuator	NavIO	Positive	Dive brake	Antenna boresight	AMPL	Flirtey
			PIC microcontroller	ARC	Anti-rolling gyro	Rigid chain actuator	PXFMini	Faster	Flap	Batwing antenna	AngelScript	Sky-Watch
			Single-board microcontroller	Atom	Control moment gyroscope	Digital electronic speed controllers	Nuttx	Slower	Gouge flap	Array gain	HyperTalk	
			Netduino	PSoC	Fibre optic gyroscope	Engines	Xenomai	Left	Air brake	Dipole antenna	Rc	
				Rockchip	Quantum gyroscope	Propellers	DDS-ROS 2.0	Up	Balanced rudder	Halo antenna	Rexx	
				InvenSense	Accelerometers	Modular propeller	KKMultiCopter	Down	Control loading system	Spiral antenna	Finite-state machine	
				Single board computers	Gravimeter	Scimitar propeller	ArduCopter	Feedback	Controllable slope soaring	Analog-to-digital converter	Alternating finite automation	
				Banana Pi	Laser accelerometer	Cyclorotor		Tailwind	Servo tab	Data link	Asymmetric numeral systems	
				Kano	Liquid capacitive inclinometers	Contra-rotating propellers		Feed forward	Autopilot	Telemetry	Buchi automation	
				P112	PIGA accelerometer	Servomotors			Helicopter flight dynamics	EMR telemetry	Krohn-Rhodes theory	
				VoCore	Inertial measurement unit	Weapons			Multirotor flight dynamics	Electronic data capture	Quotient automaton	
				Flight controller	Compass	Payload actuators				Remote data capture	Permutation automation	
				Flight controller board	Barometer	LEDs				Remote terminal unit	Behavior trees	
					GPS receiver	LED circuit				Wildlife radio telemetry	Hierarchical task planners	

LED lamp	Satellite navigation	PID controller
LED strip light	Radio transmitter	Motion planning
Speakers	Ground control station	Tree searches
	Wearable devices	and-or tree
	Electroence-phalography	k-ary tree
	Beta wave	Suffix tree
	Spike-and-wave	Radix tree
	PGO waves	Trace tree
	Evoked potential	Genetic algorithms
	Ear-EEG	Cultural algorithm
	Uplink	Fitness function
	Downlink	Genetic fuzzy systems
	Real-time video	Genetic programming
	Downstream	Truncation selection
	Smartphone	Self-level
	Tablet	Altitude hold
	Computer	Hover hold
	Human movement recognition	Headless mode
		Care-free
		Take-off
		Autoland
		Aerobatics
		Camera
		Digital camera
		Remote camera
		Still camera
		Video camera
		Range imaging

Appendix C. The result of Wikipedia-based morphological matrix after applying *subordinate value seed terms* (extended model)

Dimensions	Body	Power supply	Platform	Computing	Sensors	Actuators
Values	Tailless quadcopter	Lithium ion batteries	Battery elimination circuitry	Microtechnology	Exteroceptive sensors	Engines
	Rotorcraft	Lithium polymer batteries	Embedded systems	System on a chip	Non-cooperative sensors	Servomotors
	Rotary wing	Solid-state lithium-ion battery	Microcontroller unit	Advanced microcontoller bus architecture	Automotive safety technologies	Weapons
	Co-axial rotors	18650 battery	Embedded controller	MPSoC	Collision avoidance	Payload actuators
	Intermeshing rotors	Dual carbon battery	Arduino	Amlogic	Drive by wire	Speakers
	Slowed rotor	Graphene foam	PIC microcontroller	ARC	Child safety lock	Actuators
	Cyclogyro	Lithium hybrid organic battery	Single-board microcontroller	Atom	Shock absorber	Helical band actuator
	Mono-	Lithium ion manganese oxide battery	Netduino	PSoC	Crosswind stabilization	Linear actuator
	Bi-	Lithium iron phosphate battery	RAM image	Rockchip	Gyroscopes	Plasma actuator
		Lithium-air battery	Sensing floor	InvenSense	Anti-rolling gyro	Rigid chain actuator
		Lithium-sulfur battery	Smart camera	Deformable mirror	Control moment gyroscope	Propellers
		Lithium-titanate battery	Hardware reset	Hydrogen sensor	Fibre optic gyroscope	Modular propeller
		Lithium-ion flow battery	Bit banging	Microreactor	Quantum gyroscope	Scimitar propeller
		Nanoball batteries	Flash memory emulator	Microthermoformi-ng	Accelerometers	Cyclorotor
				Mask inspection	Gravimeter	Contra-rotating propellers
				Single board computers	Laser accelerometer	Power electronics
				Banana Pi	Liquid capacitive inclinometers	Digital electronic speed controllers
				Kano	PIGA accelerometer	Commutation cell
				P112	Inertial measurement unit	Gate driver
				VoCore	Navigational equipment	Magnetic amplifier
				Flight controller	Compass	Power module
				Flight controller board	Inertial navigation system	Power semiconductor device
					Pressure reference system	Optic diodes
					Ecompass	LEDs
					Transfer alignment	LED circuit
					Barometer	LED lamp
					Global positioning system	LED strip light
					GPS receiver	Crystal LED
					Clock drift	Flexible OLED
					Digital anchor	Phosphorescent OLED
					Vehicle tracking system	Superluminescent diode
					Positioning system	
					Pseudorange	

Dimensions	Software	Loop principles	Flight controls	Communications	Autonomy	Manufacturers
Values	Real-time	Control theory	Aircraft controls	Radio electronics	Hierarchical control systems	3D Robotics
	Raspberry Pis	Open loop	Air brake	Radio frequency front-end	Scripting language	AeroDreams
	Beagleboards	Closed loop	Balanced rudder	RF power margin	ActivePerl	DJI
	NavIO	Networked control system	Control loading system	Image response	AMPL	Flirtey

PXFMini	Adaptive control	Controllable slope soaring	Feed line	AngelScript	Sky-Watch
Nuttx	Intelligent control	Servo tab	RF probe	HyperTalk	
Xenomai	Perceptual control theory	Autopilot	Transceiver	Rc	
DDS-ROS 2.0		Helicopter flight dynamics	Radio frequency front-end	Rexx	
KKMultiCopter		Multirotor flight dynamics	Antenna	Finite-state machine	
ArduCopter		Aerodynamics	Loop antenna	Alternating finite automation	
		Plane flight dynamics	Antenna boresight	Asymmetric numeral systems	
		Aerodynamic heating	Batwing antenna	Buchi automation	
		Airspeed	Array gain	Krohn-Rhodes theory	
		Inertia coupling	Dipole antenna	Quotient automaton	
Contra-rotating propellers		Roaxial rotors	Halo antenna	Permutation automation	
			Spiral antenna	Behavior trees	
Digital electronic speed controllers			Digital signal processing	Automated planning and scheduling	
			Analog-to-digital converter	Hierarchical task planners	
			Aliasing	State space planning	
			Bandlimiting	Partial-order planning	
			Infinite impulse response	Kinodynamic planning	
Power semiconductor device			Oversampling	Multi-agent planning	
			Half-band filter	Reactive planning	
			Data transmission	PID controller	
			Data link	Robot kinematics	
			Adaptive equalizer	Motion planning	
			Backward channel	Kinodynamic planning	
			Bandwidth cap	Kinematic chain	
			Narrative traffic	Articulated robot	
			Parity bit	Passive dynamics	
Superluminescent diode			Telemetry	Serial manipulator	
			EMR telemetry	Tree searches	
			Electronic data capture	And-or tree	
			Remote data capture	K-ary tree	
			Remote terminal unit	Suffix tree	
			Wildlife radio telemetry	Radix tree	
			Satellite navigation system	Trace tree	
			Satellite navigation	Genetic algorithms	
			Timation	Cultural algorithm	
			Total electron content	Fitness function	
			Vehicle tracking system	Genetic fuzzy systems	
			Hybrid positioning system	Genetic programming	
			Automatic vehicle location	Truncation selection	
			Telecommunication equipment	Self-level	
			Radio transmitter	Altitude hold	
			Block upconverter	Hover hold	
			Hybrid coil	Headless mode	
			Radio spectrum scope	Care-free	
			Network termination	Take-off	
			Optical line termination	Autoland	
			Ground control station	Aerobatics	
			Wearable devices	Optical devices	
			Electroencephalography	Camera	

Beta wave	Digital camera
Spike-and-wave	Remote camera
PGO waves	Still camera
Evoked potential	Video camera
Ear-EEG	Range imaging
Uplink	Wright camera
Downlink	Night vision devices
Real-time video	Laser beam profiler
Downstream	Head-up display
Smartphone	Electric eye
Tablet	
Computer	
Human movement recognition	

Appendix D. The result of Wikipedia-based morphological matrix after developing sub-dimensions (extended model)

Dimensions	Body		Power supply	Platform		Computing	
Sub-dimensions		Rotorcraft	Lithium ion batteries		Embedded systems		Microtechnology
Values	Tailless quadcopter	Rotary wing	Lithium polymer batteries	Battery elimination circuitry	Microcontroller unit	Flight controller	System on a chip
	Mono-	Co-axial rotors	Solid-state lithium-ion battery		Embedded controller	Flight controller board	Advanced microcontoller bus architecture
	Bi-	Intermeshing rotors	18650 battery		Arduino	Single board computers	MPSoC
		Slowed rotor	dual carbon battery		PIC microcontroller	Banana Pi	Amlogic
		Cyclogyro	Graphene foam		Single-board microcontroller	Kano	ARC
			Lithium hybrid organic battery		Netduino	P112	Atom
			Lithium ion manganese oxide battery		…	VoCore	PSoC
			Lithium iron phosphate battery		RAM image	…	Rockchip
			Lithium-air battery		Sensing floor		InvenSense
			Lithium-sulfur battery		Smart camera		…
			Lithium-titanate battery		Hardware reset		Deformable mirror
			Lithium-ion flow battery		Bit banging		Hydrogen sensor
			Nanoball batteries		Flash memory emulator		Microreactor
			…		…		Microthermoforming
							Mask inspection
							…

Dimensions	Sensors					
Sub-dimensions		Automotive safety technologies	Gyroscopes	Accelerometers	Navigational equipment	Global positioning system
Values	Exteroceptive sensors	Collision avoidance	Anti-rolling gyro	Gravimeter	Compass	GPS receiver
	Non-cooperative sensors	Drive by wire	Control moment gyroscope	Laser accelerometer	Inertial navigation system	Clock drift
	Inertial measurement unit	Child safety lock	Fibre optic gyroscope	Liquid capacitive inclinometers	Pressure reference system	Digital anchor
	Barometer	Shock absorber	Quantum gyroscope	PIGA accelerometer	Ecompass	Vehicle tracking system
		Crosswind stabilization	…	…	Transfer alignment	Positioning system
					…	Pseudorange
						…

Dimensions	Actuators					Software	Loop principles	Flight controls	
Sub-dimensions		Actuators	Propellers	Power electronics	Optic diodes		Control theory		Aerodynamics
Values	Engines	Helical band actuator	Modular propeller	Digital electronic speed controllers	LEDs	Real-time	Open loop	Aircraft controls	Plane flight dynamics
	Servomotors	Linear actuator	Scimitar propeller	Commutation cell	LED circuit	Raspberry Pis	Closed loop	Autopilot	Aerodynamic heating
	Weapons	Plasma actuator	Cyclorotor	Gate driver	LED lamp	Beagleboards	Networked control system	Helicopter flight dynamics	Airspeed
	Payload actuators	Rigid chain actuator	Contra-rotating propellers	Magnetic amplifier	LED strip light	NavIO	Adaptive control	Multirotor flight dynamics	Inertia coupling
	Speakers	…	…	Power module	Crystal LED	PXFMini	Intelligent control	Air brake	Roaxial rotors
				Power semiconductor device	Flexible OLED	Nuttx	Perceptual control theory	Balanced rudder	…
				…	Phosphorescent OLED	Xenomai	…	Control loading system	
					Superluminescent diode	DDS-ROS 2.0		Controllable slope soaring	
					…	KKMultiCopter		Servo tab	
						ArduCopter		…	

Dimensions	Communications								
Sub-dimensions		Telecommunication equipment	Satellite navigation system	Data transmission	Digital signal processing	Electroencephalography	Telemetry	Antenna	Radio communications stubs
Values	Ground control station	Radio transmitter	Satellite navigation	Data link	Analog-to-digital converter	Beta wave	EMR telemetry	Loop antenna	Radio frequency front-end
	Wearable devices	Block upconverter	Timation	Adaptive equalizer	Aliasing	Spike-and-wave	Electronic data capture	Antenna boresight	RF power margin
		Hybrid coil	Total electron content	Backward channel	Bandlimiting	PGO waves	Remote data capture	Batwing antenna	Recurrent rotation

Radio spectrum scope	Vehicle tracking system	Bandwidth cap	Infinite impulse response	Evoked potential	Remote terminal unit	Array gain	Thermal fade
Network termination	Hybrid positioning system	Narrative traffic	Oversampling	Ear-EEG	Wildlife radio telemetry	Dipole antenna	Spurious emission
Optical line termination	Automatic vehicle location	Parity bit	Half-band filter	…	…	Halo antenna	M-ray transmission
…	…	…	…			Spiral antenna	…
						…	

Dimensions	Autonomy									Manufacturers
Sub-dimensions		Aircraft landing systems	Robot kinematics	Automated planning and scheduling	Scripting language	Finite-state machine	Tree searches	Genetic algorithms	Optical devices	
Values	Hierarchical control systems	Autoland	Motion planning	Hierarchical task planners	ActivePerl	Alternating finite automation	and-or tree	Cultural algorithm	Camera	3D Robotics
	Behavior trees	Microwave landing system	Kinodynamic planning	State space planning	AMPL	Asymmetric numeral systems	k-ary tree	Fitness function	Digital camera	AeroDreams
	PID controller	Precision approach radar	Kinematic chain	Partial-order planning	AngelScript	Buchi automation	Suffix tree	Genetic fuzzy systems	Remote camera	DJI
	Self-level	Simplified directional facility	Articulated robot	Kinodynamic planning	HyperTalk	Krohn-Rhodes theory	Radix tree	Genetic programming	Still camera	Flirtey
	Altitude hold	SCAT-I	Passive dynamics	Multi-agent planning	Rc	Quotient automaton	Trace tree	Truncation selection	Video camera	Sky-Watch
	Hover hold	Transponder landing system	Serial manipulator	Reactive planning	Rexx	Permutation automation	…	…	Range imaging	
	Headless mode	Marker beacon	…	…	…	…			Wright camera	
	Care-free	Instrument landing system							Night vision devices	
	Take-off	…							Laser beam profiler	
									Head-up display	
									Electric eye	

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