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Technological innovation for sustainable growth: An ontological perspective

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ABSTRACT

Technological innovations are seen as means to optimize the efficient and clean use of vital resources in social-biological-economic systems. However, partial theoretical perspectives and experiences of their effects can lead to significant oversight of their potential and limitations. There is a need to manage technological innovations for sustainable growth from a holistic perspective, systemically and systematically. To do so, we present and validate an ontological framework, map the current body of knowledge, and identify the emphases and gaps in the domain. The ontological framework is constructed from the common terminology of the domain. The analysis is based on a map of 375 research papers published in the most prestigious journals relevant to the domain. The results show significant gaps in the research to fulfil the potential. Future research can be directed to fill these gaps.

1. Introduction

Humanity faces an increasing and urgent need to manage scarce, natural, and vital man-made resources, such as ecology, energy, agriculture, healthcare, transportation, housing, education and many others, in the scenario of population increases and natural resource over-exploitation (Coccia, 2014; Harrison, 1998; Huesemann and Huesemann, 2008). Technological innovations are being developed in different fields to optimize the use of these resources in societies pursuing socioeconomic growth (Ayres, 1996; Jacobsson and Johnson, 2000; Tsoutsos and Stamboulis, 2005) and targeting sustainable development in bio-ecological and societal terms. The technological innovations are new means for the efficient, clean and optimal use of scarce resources (Klewitz and Hansen, 2014; Rennings, 2000). While the term sustainable development or sustainable growth was first coined at the United Nations Conference on the Human Environment in 1972 (Hall et al., 2010), the opportunities to innovate for sustainability garnered wide attention with the Brundtland report in 1987 (Eteokleous et al., 2016; Farahani et al., 2014; Govindan et al., 2014; Lukman et al., 2016), which noted the importance of firms to create, redesign, adapt, and diffuse environmentally sound technologies (WCED, 1987). In addition, this interest in the subject can be observed in the development of academic conferences on the subject. Examples of this are the IAMOT 2015 and 2016 conferences, which focused on issues concerning Technology, Innovation and Management for Sustainable Growth. Among the areas or research interests which are most studied the following stand out: Technological planning, social impact of technology, measurements Intellectual property, Industrial and manufacturing system technologies, Information and communication technology management Innovation and sustainable growth, Innovation, Education & e-learning, Management of biosciences and medical technology Management of innovation, Managing energy technologies, Managing green technology, technology and social incubation, transfer and entrepreneurship Social and technology policies, Sustainable logistics and supply chain management, foresight and forecasting Technology and globalization, among others.

This interest, which manifested in technological innovations for sustainable growth, emerged from different areas of knowledge, such as entrepreneurship, energy, policy, economics, sociology and engineering. Each has approaches, models, frameworks, and biases to study the challenges of sustainable growth. Their partial perspectives and lenses generate new knowledge in their own domains, but they are not necessarily compatible and complementary in a more holistic perspective (Hall et al., 2010). For example,

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technological innovations to use green energy or other sustainable technologies in manufacturing could be disconnected from cultural growth; the results may be constrained if appropriate educational and cultural catalyzing forces are not incorporated as part of the sustainable innovation strategy with customers and employees (Nanda and Singh, 2009). The emergence of a new knowledge area, such as the management of technological innovation for sustainable growth (MOTISG), is expected to derive from different disciplines, with the requirement of an understanding to define and develop a new discipline. In this context, connections and disconnections between research topics will affect the domain's agenda and, therefore, the harmonic development of policies and MOTISG (Nielsen et al., 2015).

The evolution of a complex domain, such as MOTISG, cannot be accomplished by simple inspection or analysis of its constituent elements. The complexity of the domain is combinatorial. It is necessary to systematically synthesize the domain knowledge, comprehensively orchestrate the efforts of the policy makers and practitioners and continuously monitor the consequences of the decisions made and actions taken. To understand, assess, plan, manage and monitor the effectiveness of strategies, policy or practices from a holistic perspective, a systematic and systemic approach is required. Thus, this paper is motivated by the need to find a holistic and comprehensive means to understand the complexity of the phenomena and design a multi-purpose and actionable tool to manage it. The central research questions of this study are as follows: a) How can one visualize MOTISG such that it allows for the analysis and synthesis of the field? b) What are the current emphases or gaps in the available knowledge? and c) How can one develop a roadmap of research to advance the domain?

To address these research questions, this paper presents an ontological framework for visualizing the combinatorial complexity of MOTISG in structured natural English. This paper then presents maps of the elements and themes of the framework that were heavily emphasized, lightly emphasized and not emphasized in the research of this domain between 1988 and 2014. Last, this paper discusses the potential reasons for and the consequences of the differences in emphases and suggests a roadmap for future research. The roadmap can be used to align the efforts of researchers, policy makers, and practitioners of MOTISG to satisfy the agendas of national innovation systems.

Many recent papers have highlighted the importance of governance and a variety of stakeholders in MOTISG (Husted and Sousa-Filho, 2017; Kang and Hwang, 2017; Niesten et al., 2017; Ramos et al., 2015; Zhu et al., 2017). These papers also propose different techniques for addressing the complexity of the domain (Disterheft et al., 2016; Uygun and Dede, 2016). The ontological framework proposed in this paper will help govern the stakeholders' competing and converging interests in MOTISG by visualizing them as part of a complex, open, socio-technical system with feedback.

2. Theoretical framework

According to Evans et al. (2017), little is known about the successful adoption of sustainable business models. When considering business model innovations for sustainability, this leads to a higher complexity related to how to preliminarily assess the impact of the sustainability innovations and how to understand their effects on the whole business network. In that sense, Edgeman and Eskildsen (2014) state that long-term firm success is a consequence of balancing both the competing and complementary interests of stakeholder segments, including society and the natural environment, in order to increase the likelihood of sustainable competitive positioning.

An interesting model used to understand the interactions between technological innovation and sustainable growth is under the view of the triple bottom line (Hart and Milstein, 2003; Schaltegger et al., 2012; Stubbs and Cocklin, 2008) where businesses must consider the co-creation of profits, social and environmental benefits and the balance among them, if they want to develop technological innovation for sustainable growth.

The sustainable value of businesses can be structured in three dimensions:

- *Environmental value forms*: Renewable resources, low emissions, low waste, biodiversity, pollution prevention (air, water, land).
- *Social value forms*: equality and diversity, well-being, community development, secure livelihood, labour standards, health and safety.
- *Economic value forms*: profit, return on investments, financial resilience, long-term viability, business stability.

For Gulati and Kletter (2005) the triple bottom line model means that "leading companies are transforming these relationships by taking a wider and longer-term view, which enable the move from a transactional mindset towards the development of trust-based, mutually beneficial and enduring relationships with key internal and external stakeholders " (as cited in Evans et al. (2017) (employees, suppliers, consumers and shareholders/investors; media; governments, universities, communities, internal organizations or local and international non-governmental organizations).

2.1. Environmental dimension

Climate change over the last few decades is evidence of the environmental degradation caused by humans pursuing economic development and of a growing population that overexploits natural resources and overestimates its technological achievements while ignoring its limitations (Bertinelli et al., 2012; Clow, 1998; Coccia, 2014). The environmental effects caused by the economic activities that consume natural resources is only one of the problems that researchers foresee leading to the collapse of social-biological-economic systems during the second half of the 21st century (Tsiliyannis, 2014). Ayres (1996) posed several questions about the kinds of technological innovations that would be needed for a truly sustainable future, highlighting that welfare may not be explained only and directly by economic growth but also by scientific and technological progress. Regarding the environmental dimension of sustainability, an eco-innovation perspective emerges as a response to the need to reduce the quantities of resources and sinks used via the incorporation of new and different technologies rather than by the novel use of old technologies (Huber, 2000). Research on sustainable innovations has expanded rapidly to increase understanding of the means by which new clean technologies (Montalvo, 2008) and social practices, such as eco-innovation (Hall and Clark, 2003), foster technological, institutional and organizational changes to the knowledge base of existing production systems to enable societies to become more sustainable. However, despite expanding knowledge, the eco-innovation concept reveals the tension among the rationales behind the economically oriented goals, ecological modernization and societal functions (Coenen and Díaz López, 2010).

2.2. Social dimension

Regarding the social and economic dimension of sustainability, companies are rethinking their relationships with key stakeholders who live in the environments in which they operate. Business strategy and management disciplines are increasingly incorporating sustainable development into their long-established assumptions and frameworks, stimulating rich, new and diverse fields of study and rethinking the theoretical foundations and the practice of business strategy (Hahn et al., 2010; Winn and Kirchgeorg, 2005). According to Evans et al. (2017), practical approaches to sustainability have been proposed with some common properties: improving sustainability often implies change, innovation or adjustment of an entity in relation to its surroundings or supporting environment. The ability to innovate in the area of sustainability represents a business capability, whether related to small incremental steps or to radical, disruptive innovations (Adams et al., 2012).

2.3. Economic dimension

Integrating sustainability into business models requires a systemic view that considers the global perspective and different elements of the system and their interrelations. This view is interesting, since welfare means economic power for an increasing population but also means improving health, educational and cultural levels, and an overall standard of living. These side effects of the economic improvements could be evidenced in the availability of leisure time; however, the prevailing socioeconomic systems that optimize the allocation of resources create wealth concentration among fewer minorities, whereas the majority works in 'unsustainable' schemes according to the broader welfare concept (Ayres, 1996). It is also evident today that wealth aggregation alone does not result in the sufficient reduction of environmental pollution (Bertinelli et al., 2012) or for all populations to have more equal access to higher living standards (Coenen and Díaz López, 2010).

Attending to the concerns of a varied nature—including environmental, social, cultural, demographic, educational, economic, technological, political and maybe more—it has been claimed that the improvement of policy and practices for the corporate, academic and governmental spheres is necessary to avert global collapse and to foster sustainable growth (Huesemann and Huesemann, 2008; Rochon et al., 2010). As a response to the dilemmas of economic development and sustainable growth, technological innovations are viewed as a source of solutions for the generation of ecologically friendly environments for producing goods and services. However, it is also recognized that technological innovations require political guidance to orchestrate ecological modernization because they do not emerge spontaneously in the right direction (Huber, 2000; Lorek and Spangenberg, 2014; Nielsen et al., 2015; Padilla-Perez and Gaudin, 2014).

The environmental, social and economic concerns for innovation become more frequent as firms are now aware of the consequences of their activities and attempt to be socially responsible. Innovations at all levels and from different sources that push and pull forces are essential when considering a transition to more sustainable forms of production, use of energy, and management (Sáez-Martínez et al., 2016). The technological capability has an important national dimension, as countries regularly devote significant resources to develop and maintain such capabilities. According to Fagerberg and Srholec (2017) there is no conflict between improving technological capabilities and emphasizing on sustainability and/or welfare at the country level.

In addition, accelerated scientific research and technological innovation cannot avert collapse without fundamental changes in society's dominant values of growth, exploitation and consumption (Huesemann and Huesemann, 2008). In the context of this complex and urgent necessity, and recognizing a lack of theory or experience that acts as a guide to policymaking (Bhat, 2005; Harrison, 1998; Nielsen et al., 2015), the current paper introduces an ontological framework to systemically and systematically guide the generation and transfer of knowledge on MOTISG.

3. Construction of the ontological framework

MOTISG is an ill-structured, complex problem. It has the divergent interest of stakeholders, and its component variables have hidden second- and third-order effects. It would be infeasible to model and optimize MOTISG with mathematical and/or statistical methods without strong *ceteris paribus* assumptions. An ontological framework is a means of structuring and deconstructing the combinatorial complexity of the problem that simultaneously creates a number of specific hypotheses and theories related to the nature and structure of reality (Guarino et al., 2009; Wyssusek, 2004). An ontology represents the conceptualization of a domain (Gruber, 2008) and organizes the terminologies and taxonomies of that domain. An ontology is an "explicit specification of a conceptualization" (Gruber, 1995, p. 908), and it can be used to systematize the description of a complex system (Cimino, 2006). An ontology simultaneously creates a number of specific hypotheses and theories related to the nature and structure of reality (Guarino et al., 2009; Wyssusek, 2004). We present a domain ontology that "helps identify the semantic categories that are involved in understanding discourse in that domain" (Chandrasekaran et al., 1999, p.23).

Ontologies and ontological analysis are widely used in computer science, medical informatics, and philosophy. These forms are not as widely used in management research. This paper's application of ontological thinking is different but not new. This paper is less structured than that in computer science and medical informatics but more structured than that in philosophy. This paper is particularly amenable to analyzing large volumes of text data about a combinatorially complex problem, such as MOTISG.

A detailed description of ontological meta-analysis and synthesis of research in mHealth is provided by Cameron et al. (2016), in eCommerce by La Paz et al. (2015) and in public health informatics by Ramaprasad and Syn (2015). The method has also been applied to the comprehensive analysis of national healthcare policies in Australia (Ramaprasad et al., 2016b), China (Dai et al., 2016), India (Sastry et al., 2017) and Chile (Núñez Mondaca et al., 2015) and to national educational policy in India (Ramaprasad et al., 2016a). The ontological framework hierarchically deconstructs (Simon, 1962) the complexity of MOTISG. The framework parsimoniously and comprehensively presents the components of MOTISG using structured natural English. In contrast, it would be lengthy and unwieldy to effectively present the full complexity of MOTISG using a linear natural-English narrative. The framework makes the complexity visible and comprehensible by providing a full view of the scope of the domain on a single page, encapsulating the potentially thousands of themes in MOTISG. An ontological framework of MOTISG is shown in Fig. 1. Three illustrative components derived from the framework are listed below; further below is the glossary of terms in the ontology.

The ontological framework of MOTISG in Fig. 1 is a three-level hierarchy. At the first level, MOTISG is logically deconstructed into five dimensions, each represented by a column. These dimensions are: (a) Management, (b) Innovation, (c) Technology, and (d) Growth. A fifth dimension—Stakeholder—is implied in the statement; it is the manager of the technological innovation for sustainable growth. Thus,

MOTISG = Stakeholder + Management + Innovation + Technology + Growth

Stakeholder		Management		Innovation		Technology		Growth	
Government	[+]	Strategies	[for]	Generation	[of]	Agriculture	[technology for sustainable]	Scientific	[growth]
Global		Policies		Incubation		Biological		Technological	
Regional		Practices		Application		Communication		Economic	
National		Monitoring		Evaluation		Education		Social	
Local						Energy		Cultural	
Industry						Industrial			
University						Information			
						Manufacturing			
						Medical			
						Tourism			
						Transportation			

Illustrative components (total = 6*4*4*11*5 = 5280):

Government$_{regional}$ strategies for generation of agricultural technology for sustainable scientific growth.
Industry practices for evaluation of global medical technology for sustainable social growth.
University policies for incubation of energy technology for sustainable technological growth.

Glossary:

Stakeholder: An entity with a stake in MOTISG.
Government: The public agency responsible for governance, regulations, law, etc.
Global: A government agency with a global coverage. For example, a UN agency
Regional: A government agency covering a segment of the globe. For example, Latin America, Africa.
National: A country's government.
Local: A state, city, municipality, village, etc. government.
Industry: Private and public enterprises which collectively produce and distribute goods and services.
University: Institution of higher education.
Management: The process of realizing technological innovation for sustainable growth.
Strategies: Systematic principles for MOTISG
Policies: Guidelines for MOTISG based on srategies.
Practices: Actions for MOTISG based on policies and strategies.
Monitoring: Assessment and feedback on outcomes of practices, policies, andd strategies.
Innovation: The intorduction of something new for sustainable growth.
Generation: Generation of a new idea or artifact.
Incubation: Nurturing of the new idea or artifact.
Application: Translation of the new idea or artifact into practice.
Evaluation: Assessment of the new idea or artifact in practice.
Technology: The domain of innovation.
Agriculture: Farming for crops, animals, fish, etc.
Biological: Innovations about/based on the biology of plants, animals, and people.
Communication: Innovations for exchange of information between people, organizations,etc.
Education: Innnovations for the generation, transfer, and application of knowledge.
Energy: Innovations related to the production, distribution, and use of different forms of energy.
Industry: Innovations related to the production and distribution of goods and services.
Information: Innovations related to the techologies and systems used for information processsing.
Mnaufacturing: Innovations related to the production of goods.
Medical: Innovations related to the delivery of healthcare services.
Tourism: Innovations related to the services for visitors.
Transportation: innovations related to the movement of people and goods.
Growth: The type of sustainable growth catalyzed by innovation
Scientific: Growth in scientific knowledge for sustainable growth.
Technological: Growth in sustainable technology.
Economic: Sustainable growth of the economy.
Social: Sustainable social advancement.
Cultural: Sustainable cultural advancement.

Fig. 1. Ontology of the management of technological innovation for sustainable growth.

In the language of open systems theory (Emery, 2004), Management and Innovation are internal dimensions of the framework; Stakeholder, Technology, and Growth are the environmental dimensions. The framework represents the interaction of these internal and environmental dimensions. Similarly, in the terminology of socio-technical systems theory (Katz and Kahn, 1978), Technology is the technical dimension, and the others are the social dimensions. The framework represents the combinatorial combination of the social and technical dimensions in MOTISG. Last, from the cybernetics theory (Anderson, 1999), feedback (Ramaprasad, 1983) is built into the definition of the Management and Innovation dimensions. The definition provides the feedback to guide MOTISG.

At the second level, a taxonomy of its constituent elements expresses each dimension of the ontology.[1] The third level consists of subcategories of some elements.

The five taxonomies are derived from the common terminology in the body of knowledge on each dimension, particularly in the MOTISG domain. One element (Stakeholder-Government) is subcategorized to achieve a finer specificity in the construction and definition of the elements of MOTISG. Others could also be subcategorized as appropriate.

The three primary stakeholders in the ontological framework of MOTISG are the Government, Industry, and University—the three components of what is called the Triple Helix (Etzkowitz, 1989; Etzkowitz and Leydesdorff, 1995, 1998, 2000; Leydesdorff, 2005; Ranga and Etzkowitz, 2013). The Government is further subcategorized as Global, Regional, National, and Local, highlighting the potential importance of each of these on MOTISG. The three primary stakeholders are presented in no particular order. The stakeholders could be organized in order of priority in a context. If, for example, the Industry is taking the lead, followed by the Government and University, the order could be changed accordingly. The subcategories within the Government are in a general hierarchical order. Although each level may be independent, with reference to MOTISG, the lower levels may inherit certain attributes (for example, Policies and Practices) from the higher level. Thus,

Stakeholder ⊂ (Government (Global, Regional, National, Local), Industry, University)

The taxonomy of Management consists of Strategies, Policies, Practices and Monitoring. The framework explicitly includes Monitoring in recognition of the importance of feedback and control to measure management performance and results. Decisions and actions, which are often seen as following from strategies and policies, are subsumed under Practices. They could be separated in a future ontology should the distinction between the two be important for studying MOTISG. Thus,

Management ⊂ (Strategies, Policies, Practices, Monitoring)

The taxonomy of Innovation derived from the literature includes Generation, Incubation, Application and Evaluation of an innovation. These taxonomies are generally sequential and cyclical stages in innovation. Each step follows the other with feedback from Evaluation informing Generation and the subsequent stages in the subsequent cycle. There is also likely to be a significant reduction through selection at each stage. Learning about MOTISG will be facilitated by effective feedback from Evaluation to the earlier stages. Thus,

Innovation ⊂ (Generation, Incubation, Application, Evaluation)

The taxonomy of Technology is grounded in the literature of the domain and covers nearly all the significant areas. The taxonomy lists the focus of innovations in MOTISG. The taxonomy is presented in alphabetical order and could be reordered by priority in a context. The list could also be extended by adding new elements, contracted by eliminating some, refined by adding sub-elements, and coarsened by combining elements. Through these mechanisms, one can adjust the scope and granularity of the taxonomy. Thus, Technology ⊂ (Agriculture, Biological, Communication, Education, Energy, Industrial, Information, Manufacturing, Medical, Tourism, Transportation)

[1] Words that refer to the dimensions of the ontology are capitalized. References to elements of a dimension are also capitalized.

Last, sustainable Growth is articulated as a composite of Scientific, Technological, Economic, Social and Cultural Growth. These categories are nominal and are presented in the general order they are referred to in the domain. The underlying assumption is that the overall sustainability is dependent on these different sustainabilities, not simply one or two. The order can be changed to fit the priority in a context. Thus, Growth ⊂ (Scientific, Technological, Economic, Social, Cultural)

The five dimensions are arranged left to right with adjacent symbols, words, and phrases such that reading left to right, concatenating an element from each dimension, forms a natural English sentence that represents a specific component of MOTISG. Each component may be a potential research issue and an area for knowledge generation and transfer. Three illustrative components are shown below, and the subcategories of a taxonomy are shown as subscripts. The components are as follows:

1. Government $_{\text{regional}}$ strategies for the generation of agricultural technology for sustainable scientific growth;
2. Industry practices for the evaluation of global medical technology for sustainable social growth; and
3. University policies for the incubation of energy technology for sustainable technological growth.

These three and 5277 others encapsulated in this ontology are logically the potential components of MOTISG. Listing these components individually would require hundreds of pages, hence, the parsimony of the ontological framework. The ontology presents the combinatorial complexity concisely and, thus, helps one systematically take a systemic view of the problem of MOTISG. At the same time, the ontology is plastic and could be extended (scaled) or simplified by adding or removing columns and categories in the taxonomies.

A component may or may not be instantiated or researched in a context; it may also be instantiated partially, as a fragment. Studying across contexts, some components (or fragments) may be observed frequently, some infrequently, and others not at all. Similarly, some components (or fragments) may be researched frequently, some infrequently, and others not at all. We will label the frequently instantiated/researched components the ‘bright’ spots, the infrequent ones the ‘light’ spots, and the overlooked ones the ‘blind/blank’ spots.

One may argue that the 'luminosity' of each spot is a product of two opposing dynamics. A ‘bright’ spot may be so because it is effective and important, for example, the study of green productive technologies to reduce CO_2 emissions or the optimization of productive chains to minimize wastes, but it may also be a consequence of habit and herd effect, irrespective of whether it is effective or important. A ‘light’ spot may be so because it is ineffective, untimely, and unimportant; it may also be a consequence of the difficulty of implementing or studying it, irrespective of its potential effectiveness or importance. A ‘blind/blank’ spot may have been simply overlooked by design or by accident, or it may be infeasible and spuriously produced by the combination of the elements of the ontology.

Knowing the ‘bright’, ‘light’, and ‘blind/blank’ spots in practice and research and the antecedents for these components will help develop more systemic and systematic approaches to the challenge of MOTISG. In the following, we present an ontological map of research in MOTISG in the past years, highlight the ‘bright’, ‘light’, and ‘blind/blank’ spots and discuss possible reasons for the same. Before presenting the results, we will first describe the method we used for mapping. In the conclusion, we will present the potential implications of this program of research and the planned extensions to what is presented here.

4. Research method

To identify the ‘bright’, ‘light’, and ‘blind/blank’ spots in the literature of MOTISG, a systematic search was performed on Scopus for all articles with the terms ‘technology AND innovation AND sustainable AND growth in Title, Abstract, and Keywords’. Scopus is an extensive curated database managed by Elsevier. The search term was finalized after experimenting with a few alternatives and perusing the results in the subject areas of ‘Social Sciences & Humanities’. The objective of the researchers was to be comprehensive in the coverage of the articles.

The search yielded 375 articles published from 1988 to 2014. The research was begun in 2015; hence, 2014 was chosen as the publication cutoff date. One may not be able to assert definitively that all the articles published in the period were included; however, one can be reasonably certain of the comprehensiveness of the results. The results included all the relevant articles from *Technovation, Technological Forecasting and Social Change, Ecological Economics International Journal of Sustainable Development and World Ecology, Journal of Cleaner Production, Technology in Society, Research Policy* and journals in similar domains. These 375 papers represent the population of articles relevant to MOTISG in the search period for this research. The titles and abstracts of the articles were downloaded into an Excel tool developed by one of the authors to aid coding. Using the tool, a coder can map each article based on the title and abstract to the elements of the ontology it addresses.

The number of articles per year on MOTISG has increased from approximately three or less per year before 1998 to more than 30 per year after 2009. The year 2013 appears to have been unusual with 51 articles. The rise is an indicator of the increasing importance of the topic. The trend is positive and appears likely to continue, as shown in Fig. 2.

A first coding of the data on the ontological framework was performed on a small subset of the papers to train two research assistants (Master's students) and to refine the glossary. Then, half of the population of articles was coded based on a consensus of two assistant-coders using the glossary and the aid of their supervising instructor (one of the authors of this study). If the coders' coding agreed, it was finalized as such by the instructor. If the coding disagreed, the final coding was based on a discussion between the instructor and the two coders. A second team (second instructor also author of this study and two other research assistants) revisited the mapped data and finalized the coding of the population of 375 articles in the period of observation, using the same mechanism of independent coding and discussion for agreement on the mapping of each article.

The coding process also helped validate the ontological framework and the glossary. The coders could capture the themes of the articles within the framework using the glossary. It was not necessary to expand the taxonomies or to exclude articles because they did not fit.

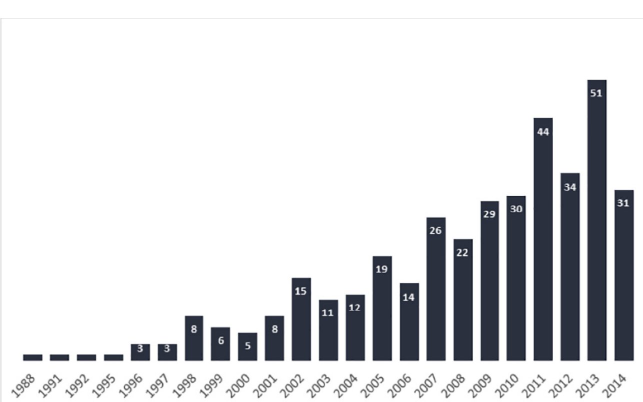

Fig. 2. Frequency of publications per year in MOTISG.

One must note that an article may instantiate multiple components, a component, parts of multiple components, or part of a component of the ontology. Thus, there was no restriction on how many elements of the ontology could be encoded with reference to an article or a requirement that an article should be encoded with reference to all the dimensions of the ontology. Thus, an article could be encoded to (a) an element from each dimension, (b) multiple elements from each dimension, (c) an element from some dimensions, or (d) multiple elements from some dimensions.

One must also note that the coding was binary, whether the element (or its synonym) was present or not in the title and abstract. The coding was not weighted; each article and each element was assigned equal weight.

To analyze the mapped data, two main types of visualizations were produced. First, the frequency of occurrence of each element (monad) in the ontology was shown using the same Excel tool. Second, the association between the elements in the corpus was presented as a dendrogram based on cluster analysis using SPSS. These visualizations are presented and discussed in the section below. We used cluster analysis to analyze the co-occurrence of elements in the ontology in the components. We used it to visually summarize the data about the corpus (population of papers) but not to make statistical inference about the population from a sample of papers.

The clusters are formed based on the coding similarity between pairs of ontology elements in the corpus measured by the simple matching coefficient (SMC) (Sokal and Michener, 1975). SMC is a symmetric similarity measure that considers presence (coded as ‘1’) and absence (coded as ‘0’) of elements in the articles (Cheetham and Hazel, 1969; Gower, 1971). In ontological analysis, both the presence and absence of elements in the corpus convey equally important information. The denominator in the SMC formula is a fixed number that represents the total number of papers coded. SMC will thus provide a more consistent comparison across pairs of elements than other measures.

The clustering was conducted in SPSS based on the Single Linkage (or Nearest Neighbor) between the clusters. The single linkage method, as the name implies, links cluster elements based on the nearest neighbor in the existing clusters. The computation in this method is simple; consequently, the agglomeration coefficients of and the dendrogram from the cluster analysis can be translated to the data and interpreted as presented, which is discussed below. This is not the case with the Centroid method, for example. Thus, the method provides an isomorphic visualization of the association between the ontology elements. These associations can be interpreted in conjunction with the frequencies of the elements in the ontological map.

5. Results

In the following, the ontological map of monads and a dendrogram of clusters for MOTISG is presented. Subsequently, the results and limitations of the study are discussed. Last, a summary of the findings and plans for extending the research are presented.

5.1. Ontological map of MOTISG monads

The ontological map of monads for all the 375 articles is shown in Fig. 3. The numbers in parentheses adjacent to the dimension and element names are the frequency of their occurrence in the corpus of 375 articles. The length of the bar under each element is

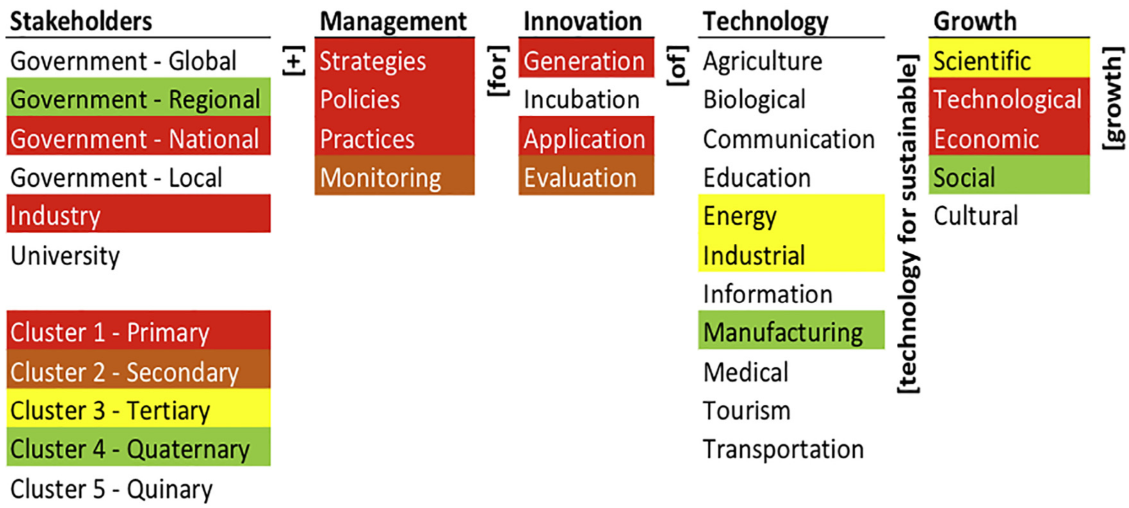

Fig. 3. Ontological map of MOTISG monads.

scaled to the maximum count in the ontology (Growth - Technological - 236). The frequency of occurrence of a dimension may be less than the sum of the frequencies of its constituent elements; an article may be coded for multiple elements of a dimension. For example, Stakeholders are coded in 355 articles, but the stakeholder elements are coded (25 + 40+143 + 32+222 + 25 = 487) times. In the following, the relative emphasis on the five dimensions and the elements within them is discussed.

The dominant dimensions in descending order are Management (365), Growth (359), Stakeholders (355), Innovation (356), and Technology (264). The relatively lower frequency of Technology suggests that many articles discuss MOTISG without reference to a technology.

The dominant stakeholders are Industry (222) and Government-National (143). The others, which are mentioned relatively less mention in the research, are Government-Regional (40), Government-Local (32), Government-Global (25), and University (25). The low frequency of University is particularly surprising since they are often viewed as the engines of technological innovation, independently and in collaboration with industry and government.

The emphasis on the four Management (365) elements is nearly uniformly distributed and is as follows in descending order: Policies (141), Strategies (140), Practices (137), and Monitoring (125). The corpus appears balanced on this dimension.

In contrast to Management (365), the emphasis on the different phases of Innovation (356) is skewed. The dominant focus is on Generation (215), followed substantially behind by Application (167), Evaluation (98), and last, with very minimal emphasis, Incubation (14). The minimal focus on Incubation (14) may be a significant gap in progressing from Generation (215) to Application (167). The limited focus on Evaluation (98) may significantly affect both feedback and learning.

Technology (264), as noted earlier, is the least frequently noted dimension. Within Technology, there is significant variation among the elements. The dominant technologies are Industrial (94) and Energy (69). Next in emphasis are Manufacturing (43), Information (34), Agriculture (33), Biological (30), and Communication (26). The least emphasis is on Education (16), Transportation (16), Medical (11), and Tourism (4). The distribution appears to be at variance with the perception of the most important technologies today.

The dominant focus of Growth (359) is Technological (236) followed closely by Economic (198). Scientific (76) and Social (55) trail behind at a considerable distance. Cultural (4) is barely noted. The emphasis on the different types of growth is highly skewed.

5.2. Dendrogram of MOTISG clusters

The dendrogram in Fig. 4 visually depicts the matching of the ontology elements in the corpus of papers based on the SMC. At the top are the two most infrequent elements in the ontological map—Tourism (4), Cultural (4), and Medical (11). The SMCs of these elements (0.979, 0.965) indicate the following: (a) no matched presence of Tourism and Culture and their matched absence in 367 articles and (b) 1 matched presence of Tourism and Medical and 361 matched absences of the two. At the bottom are the two most frequent elements in the ontological map: Economic (198) and Generation (215). Based on the SMC of these elements (0.581), one can compute that they have matched presence in 133 papers and matched absence in 85 papers. In the remainder (157), one is present. One may compute similar values for each pair of joined elements based on their frequency of occurrence (from the ontological map) and their SMC (from the dendrogram).

It may be observed in the dendrogram that (a) the less frequently present elements in the ontological map are at the top, and the more frequently present elements are at the bottom; and (b) the adjacent elements on the vertical axis are more closely matched than distant ones. By using the five equidistant divisions of SMC on the horizontal axis, the following themes in descending order of dominance in the program corpus can be inferred. Considering that more divisions will result in finer-grained themes, fewer divisions will result in coarser-grained themes. The divisions are as follows:

1. Government-National/industry strategies/policies/practices for generation/application of technology for sustainable technological/economic growth;
2. Monitoring for evaluation of technology for sustainable growth;
3. Energy/industrial technology for sustainable scientific growth;
4. Government-Regional management for innovation of manufacturing technology for sustainable social growth; and
5. Government-Global-Local/University incubation of agriculture/biological/communication/education/information/medical/tourism/transportation technology for sustainable cultural growth.

The themes are represented visually in Fig. 5. The red elements

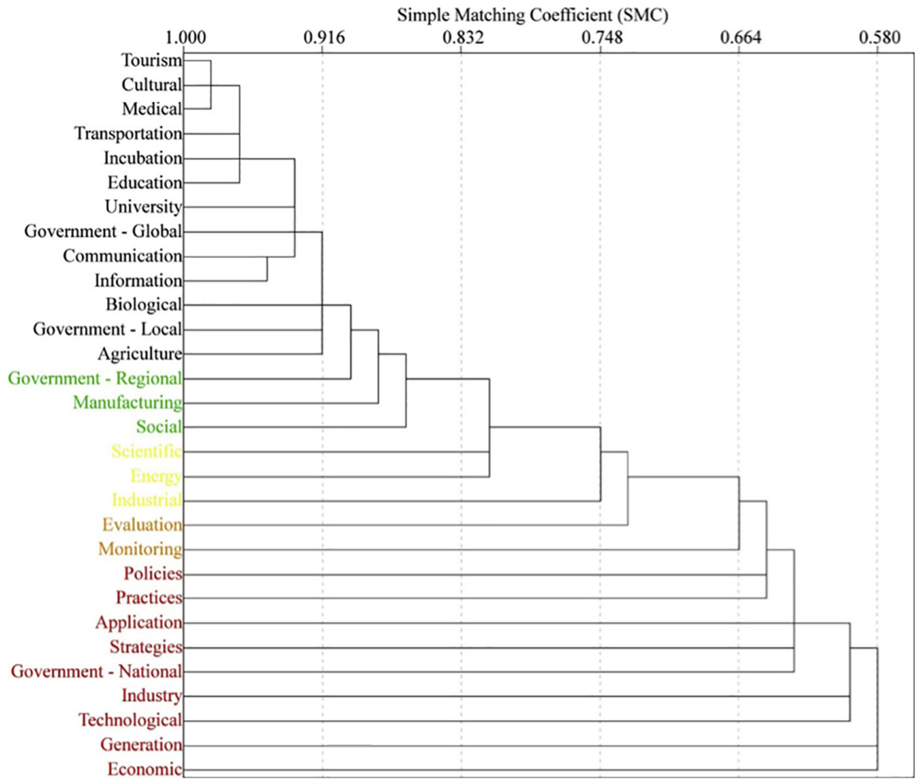

Fig. 4. Dendrogram of MOTISG clusters using single-linkage and simple matching coefficient.

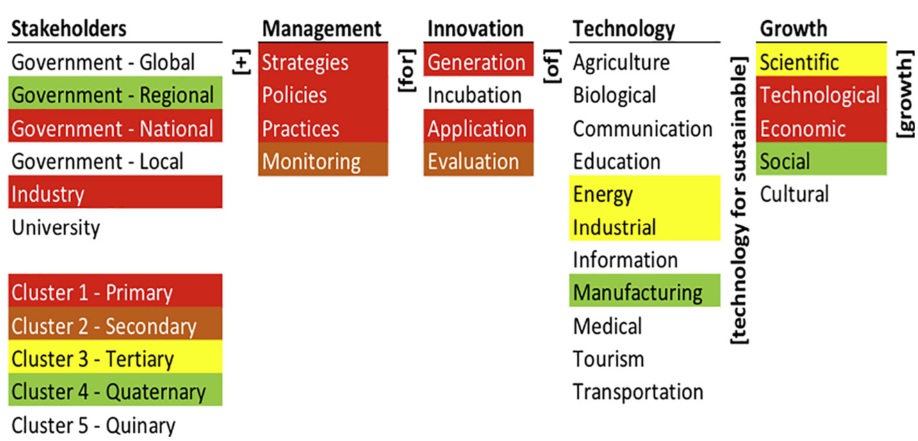

Fig. 5. Ontological map of MOTISG themes.

belong to the first cluster and the orange elements to the second. The yellow elements belong to the third, the green elements to the fourth and the non-highlighted elements to the fifth. The first two may be said to be the dominant themes of the corpus, the 'bright' spots. The next two are non-dominant themes, the 'light' spots. The last is truly a non-theme rather than a theme, highlighting what is virtually absent from the corpus, the 'blind' spots. There are no 'blank' spots. The last has many potential themes that should or could be critical for MOTISG but are absent. The next section discusses the above results and their limitations.

6. Discussion

The ontological framework is a structured natural English representation of the system required for MOTISG. The framework encapsulates the logic of MOTISG. The logic can be easily read and validated by researchers, policy makers, and practitioners. Thus, the framework is easy to understand and apply and is an easy vehicle to translate between research, policy, and practice. Each component derived from the framework can be (a) a descriptor of a MOTISG system, (b) an explanation of such a system's function/dysfunction, (c) a predictor of the system's performance, or (d) an instrument for controlling the system's performance. Whether a component is used as a descriptor, explanation, predictor, or controller would depend on the state of the knowledge about the component—control would need the most advanced knowledge, description the least. The ontological maps, coincide with bibliographic and bibliometric analyses (Carvalho et al., 2013; Fagerberg et al., 2012), showing that the knowledge within the domain is very uneven. The maps do not show how advanced the knowledge is regarding a particular component. The state of the knowledge can be ascertained from the corpus as incorporated in a subsequent study.

The ontological maps of the monads and themes in the research corpus highlight the relative emphases on the different elements and components of the framework. These maps do not indicate the reasons for the differences in emphases or the consequences of the same. The latter are epistemological issues that need to be addressed in subsequent research. In the following, some of these issues are highlighted.

The MOTISG corpus is fragmented and skewed. The corpus must be rebalanced for the research to lead to meaningful MOTISG. To rebalance is not to emphasize all the components of the framework equally. Instead, rebalancing is to consider all the components and determine their priority based on, and for, research and practice. Evans et al. (2017) indicate the use of two criteria to explain the differences observed in the literature as classification schemes with no explicit criteria, and theoretical typologies including ad hoc criteria. The ontology of MOTISG aims to make a systemic and systematic description of the field.

National governments and industry can be key catalysts of MOTISG. Universities, regional governments and local governments can be significant factors, too. While there is focus on regional governments, there is minimal or no focus on universities and local governments. The exclusion of universities contradicts the Triple Helix model (for example, Ranga and Etzkowitz, 2013) or the social and environmental value forms indicated in the triple bottom line model (Hart and Milstein, 2003; Schaltegger et al., 2012; Stubbs and Cocklin, 2008). One may argue that correcting these blind spots and bringing Triple Helix and the sustainable business model research into the study of sustainable technological innovations will be critical to effective MOTISG as well as impactful knowledge development for innovation systems. It is conceivable that there is research on these stakeholders in the broader context of technological innovation but not particularly focused on technological innovation for sustainable growth.

The high emphasis on all elements of Management is a very positive sign for the advancement of the domain. It is important to note that Monitoring is closely matched with Evaluation (in the Innovation dimension), which is as it should be. Ideally, in the future, research on the four Management elements should be extended to the stakeholders (Government-Global/Local, University) and innovation phase (Incubation) that have been overlooked in the current corpus.

A glaring 'blind' spot in the Innovation phases is on Incubation. This oversight is particularly surprising given the widespread development of incubators to foster innovation. It is possible that research on incubation has focused broadly on technological innovation but not on application of these innovations to sustainable growth. It may also occur that such blindness continues to generate and produce more of the unsustainable growth achieved until now.

The relatively infrequent and low emphasis on elements in the Technology dimension would be sensible if one assumes that MOTISG is technology agnostic. While there may be aspects of MOTISG common to all technologies, it would be reasonable to expect significant differences between them. For example, Medical and Education technologies are likely to be very different. Ideally, the corpus has to both differentiate between these technologies and integrate the knowledge about them, since the traditional innovations have been ineffective, slow and extremely resource-consuming (Contopoulos-Ioannidis et al., 2003). The current corpus' focus appears to be primarily on aspects of MOTISG common to most technologies but not necessarily on aspects particular to each that may speed up their efficient and sustainable innovation. Our approach to thoroughly describe the broad spectrum of MOTISG could facilitate the process of experimentation (Evans et al., 2017) in order to discover sustainable business models by giving systemic visibility to yet unexplored areas and to make informed simulations and reduce the costs and risks of experimentation.

Technological, Economic, and Scientific growth are necessary but not sufficient for sustainable growth. Corresponding Social and Cultural growth of the socio-cultural milieu of the first three are equally important (Carvalho et al., 2013). The corpus focuses minimally on Social growth with nearly no focus on Cultural growth, often noting the concepts, but barely scratching its surface to explain their meaning, specific mechanisms or models and impacts. The latter 'light' and 'blind' spots are critical weaknesses in the corpus.

Based on the current data, it would be difficult to provide reasons for the positive and negative biases in emphases. The relative emphases on the different elements and themes in the ontology may be partly due to conscious choices and partly due to unconscious decisions. The emphases may partly be a consequence of history and a positive 'herd' effect; more of the same research continues to be done because of the ease of doing so and getting it published. The emphasis may also partly be a consequence of oversight and a negative 'herd' effect, the difficulty of starting a new line of research and getting it published. The difficulty may also arise from the assumption that related research from other domains (for example, on Incubation) can be easily translated to MOTISG and hence is not necessary to be repeated or replicated. Irrespective of the reasons, the portfolio of research on MOTISG must be rebalanced for it to be effective. The corpus cannot provide adequate guidance for the governance of MOTISG or the management of its stakeholders (Husted and Sousa-Filho, 2017; Kang and Hwang, 2017; Niesten et al., 2017; Ramos et al., 2015; Zhu et al., 2017). The ontological framework and the method of meta-analysis of research in the domain, however, can be used to correct the inadequacy.

The ontological framework and the maps provide a basis for developing a roadmap for future research. One could consider each component of the framework as a proposition for research, assess the state-of-the-research regarding the same, and determine the priority that should be assigned to follow up with a research study. Some of the gaps that have been highlighted appear to be unquestionably important and should be part of the future research agenda. The importance of other components may vary by context and depend upon the stakeholders. The framework and the maps provide a basis for structured brainstorming about the domain. Structured brainstorming, as opposed to unstructured brainstorming, has two advantages: it can reduce potential biases due to 'more of the same' and due to 'errors of omission'. By questioning the rationale and the importance of the 'bright' and 'light' elements and components, one can assess the importance of their continuity for the future. Similarly, by inquiring into the 'blind/blank' elements and components, one can incorporate them into the research agenda.

The current analysis and results do not explore the interaction among the elements of a dimension. For example, the Triple Helix model is based on interactions between the Government-Industry-University (Etzkowitz, 1989; Etzkowitz and Leydesdorff, 1995, 1998, 2000; Leydesdorff, 2005; Ranga and Etzkowitz, 2013). Similarly, one may investigate the interaction among the sequential stages of Innovation (Godin, 2006), nonlinear innovation processes (Leydesdorff et al., 2013) and different types of Growth. The very limited emphasis on University, Incubation, and Cultural growth may critically undermine the effectiveness of MOTISG by overlooking a key Stakeholder, ignoring a necessary stage of Innovation and the very Cultural context of the sustainability construct. The framework and the data permit analysis and interpretation of such interactions in future research.

7. Conclusion

This paper makes three major contributions. This paper provides (a) a systematic and systemic framework for MOTISG; (b) a method of mapping the state-of-the-research in MOTISG; and (c) insights about the 'bright', 'light', and 'blind' spots in the domain, thus, positioning the complexity of MOTISG in the current literature and eliminating strong *ceteris paribus* restrictions to describe, analyze, model, and evaluate the variables and correlations. The ontological framework and map of MOTISG themes can be used to develop a roadmap for future research and balance the production of basic and applied knowledge on technological innovations according to the relevance and potential impact on sustainable growth. The framework and map will help assess the state-of-the-research and redirect the trajectory for the future.

The same framework and a similar method can be used to map the state-of-the-practice of MOTISG. Instead of research papers, the corpus for the state-of-the-practice can include policy and practice documents of the various stakeholders. Maps of the state-of-the-practice can be used to assess the gaps within it as well as the gaps between the states of the research and practice. The gaps between the two states will highlight the issues in translating research to practice and practice to research MOTISG. Bridging the translation gaps can help make both research and practice more effective.

In conclusion, certain limitations of the research must be highlighted. Despite best efforts, the ontology may be incomplete or over-specified. There is reasonable confidence, based on the study of the corpus while coding, that the errors of omission and commission are minimal. In the future, should it be necessary, the ontology can be extended, reduced, refined, or coarsened as appropriate.

The results are based on the population of articles on MOTISG from Scopus. There may be research not included in Scopus that may be relevant. Similarly, there may be research (for example, on innovation) not selected by our search criteria and hence excluded from coding. In the future, the domain could be systematically broadened to be more inclusive.

Considerable effort has been expended in the construction of the glossary and the monitoring of coding to minimize errors. While the coders attempted to remain true to the text of the title and abstracts without imputing their own expectations, one cannot exclude the possibility of over-coding and under-coding. Given the large population or articles (375) and the significant variation in the frequency of the elements, despite the potential errors, the results are likely to be robust.

Given the data, errors in the ontological map and dendrogram are unlikely. Adding subsequent articles to the corpus may slightly change the patterns but not significantly. However, there is room for variation in the interpretation of the luminosity of the different elements and the determination of clusters. Since the method of construction of the map and dendrogram are completely transparent, it would be easy to compare different interpretations of the same.

In summary, despite the limitations, the insights are strong. The explanations of the insights as to why the corpus is as described may vary, but there is minimal room for variation in the description of the MOTISG corpus.

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