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Exploring Opportunities for Circular Supply Chains Arising from Renewable Chemical Feedstocks

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Abstract

The aim of this research is to provide an integrated framework for supporting the design of commercially viable supply chains (SCs) towards delivering value-added intermediates or end-products based on renewable chemical feedstocks. To that end, we first provide the inclusive hierarchical decision-making process that applies to all stakeholders involved in the design and management of circular SCs arising from renewable chemical feedstock platform technologies. We then propose a framework that captures SC configuration opportunities based on four essential pillars including: (i) renewable chemical feedstocks, (ii) production process technologies, (iii) markets, and (iv) value and viability. We conclude by identifying key elements that need to be considered for ensuring the viability of the defined circular supply networks.

Keywords: Circular Supply Chain Design and Management; Renewable Chemical Feedstocks; Decision-making Process; Supply Chain Viability

1. Introduction

The circular economy era fosters metabolisms and reconfiguration opportunities across supply chains (SCs) that allow for the establishment of competitive, self-sustained and viable industrial systems (Lieder and Rashid, 2016). The aforementioned shifts are mainly dictated by the global intensification of the resource-intensive manufacturing activities (Mousavi, 2016), the alarming depletion rates of natural resources (Pleissner, 2015), and the consumers' ecological awareness. Especially, in the chemical industry, cost-efficient compounds that rely upon sustainable feedstocks are gaining an emerging role as substitutes for petroleum-based raw materials in a range of industrially manufactured products like pharmaceuticals and electronics (Kawaguchi, 2016). However, a plethora of challenges, such as feedstock demand and price fluctuation, subsidies, tax, policy and legislation, impedes the development of sustainable industries (Anuar and Abdullah, 2016). Therefore, the present paper outlines an approach that addresses the following research question: *How should global firms navigate viable SC configuration options arising from renewable chemical feedstock platform technologies?*

To that end, circular economy exerts considerable pressure on the frontiers of environmental sustainability by emphasising on the transformation of products in a way that workable relationships among ecological systems, economic growth and social wellbeing are promoted

(Genovese, 2016). Evidently, the transition from petrochemical-based feedstocks to renewable alternatives in a viable manner is one of the strategic objectives for sustainable SC management (Walker, 2014). In this sense, the European Petrochemical Association and the European Chemicals Industry Council suggest that improving sustainability in chemical SCs could increase business competitiveness (McKinnon, 2004). The global chemical industry has recorded a remarkable growth in terms of output, from US$ 171 billion in the 1970's to US$ 4.12 trillion in 2012 (UNEP, 2013). However, the chemical industry is primarily relying on crude oil-based feedstocks (Keim, 2010), while the petrochemical sector amounts for over 30% of the global industrial energy usage (Brown, 2012) and generates around 18% of the direct industrial CO_2 emissions, excluding electricity production (Benchaita, 2013).

Furthermore, the globalized marketplace and the prevalence of customised demand functions within the chemical industry increase the complexity of chemical SC operations (Li, 2016), thus highlighting the need for approaches that foster the design, analysis and assessment of supply networks involving renewable feedstocks. A great challenge in the field of SC management is the myopic view towards chemical industry due to its reliance on vertically integrated feedstock supply systems based on local supply context within high yield regions (Lamers, 2015). On the other hand, exploiting renewable chemical feedstocks increases the complexity of four identified elements in SC configuration (Srai and Gregory, 2008): (i) tier length of complete network structure, (ii) principal unit operations, manufacturing and scale up challenges involving new process technologies, (iii) stakeholders' relationships and management of chemicals' suppliers, and (iv) network value and end-product composition. Therefore, an increased need for a methodology to prioritize renewable chemical feedstocks and understand relevant SC configurations with corresponding environmental sustainability, social impact and economic viability potential exists.

The aim of this paper is to provide a theoretically derived framework to analyse SCs from compound perspective, and identify key elements that affect the economic viability of the circular supply networks. In this respect, this work synthesizes the existing literature on SC design options based on renewable chemical feedstocks in order to: (i) analyse the related decision-making process to derive factors to be evaluated in order to propose a framework for the design of renewable feedstock class defined SCs, and (ii) identify the prevalent elements that define the viability of circular SCs.

The remainder of the paper is structured as follows. In Section 2, we provide a critical synthesis of scientific publications focusing on the design of supply networks. In Section 3 we describe the research methodology applied for the purposes of this study. In Section 4, we propose a comprehensive hierarchical decision-making process for the development of circular SCs arising from renewable chemical feedstock platform technologies delivering intermediates or end-products. Following, in Section 5 we present a renewable feedstock SC analysis framework and we further summarize basic elements impacting the viability of circular SCs under study. Finally, conclusions and recommendations for future research are discussed in the last section.

2. Supply Chain Perspective

In order to identify the current state of research on SCs that are based upon renewable chemical feedstocks, we first investigated the generic classification of SC studies based on the primary perspective of the studied network operations. Notably, our search through the terms "supply chain types" and "supply chain classification" in the Scopus database revealed a lack of studies providing any categorization of SC networks. To that end, we further proceeded to a review of research efforts by using combined search criteria of the terms "supply chain" and "case study" in order to identify the main scoping elements of existing works. Therefore, Table 1 briefly summarizes selected publications in the SC domain according to the primary research scope of the investigated supply networks.

Table 1 Supply chains' classification

Scope	Selected References
Company	Cheng and Wang (2016); Hasani and Khosrojerdi (2016)
Industrial System	Dadhich (2015); Kumar (2013)
Product	Bottani (2015); Kulak (2016)
Source	Grivins (2016)
Technology	Aqlan and Lam (2016); Bergesen and Suh (2016)

Our findings reveal that the traditional SC theory considers supply networks mainly from company focus, industrial system and/or product level perspectives. However, sustainable SC management has to overcome the myopic view of existing literature and extend the focal point of analysis to renewable chemical feedstocks in order to support the development of sustainable industrial systems. To this effect, renewable chemical feedstock class defined SCs need to extend the scope of traditional SC theory and focus on: (i) source of feedstock (Bohmer, 2012), (ii) intermediates/end-products (Behr and Johnen, 2009), and (iii) processing technology and synthesis routes (Xu, 2012).

3. Research Methodology

This study is grounded on a synthesis of the existing literature that involves the combination of scientific publications for comprehensively addressing the enunciated research question (Levi and Ellis, 2006). Therefore, we conducted a critical synthesis on SC design for the case of renewable chemical feedstocks in order to map the prevalent involved parameters from a supply network perspective. The latter denotes that the literature synthesis focuses on peer-reviewed articles that address design and management aspects of SC networks.

To identify relevant papers, Boolean searches using appropriate keywords in the Scopus and Web of Science databases were carried out. In particular, the terms "renewable feedstock", "renewable chemical feedstock" and "biorefinery" were searched either separately or in combination with the terms "supply chain" and "supply chain management" by using either the "Article Title" or "Article Title, Abstract, Keywords" categories. The data range was set from "All years" to "Present", while all document types and subject areas were selected. After a first check of the contents, collected articles were accepted or rejected in terms of further review. More specifically, the analysis was restricted to journal papers written in English that focus on SC design. To increase consistency, all papers were counterchecked.

By June 13, 2016, a total of 42 articles concerning renewable chemical feedstocks and SC design had been identified. The annual allocation of the retrieved publications over the last years is depicted in Figure 1. Although the research period was not restricted, the first published case study is detected in 2009. In addition, a remarkably increasing number of related publications is documented during the period 2012-2015, hence highlighting a growing interest in the field.

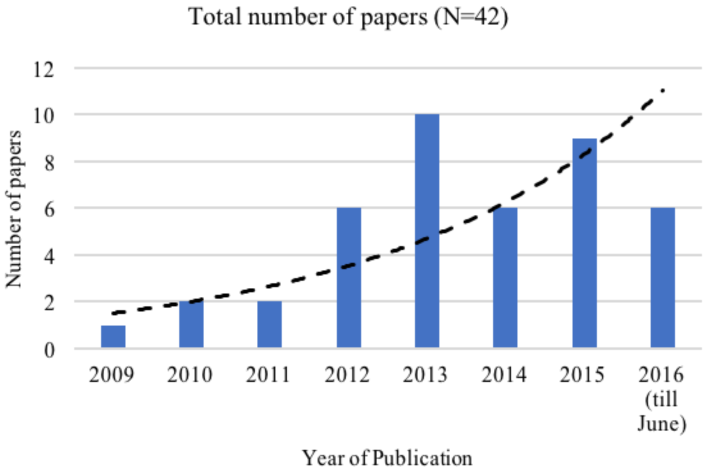


Figure 1 Distribution of publications per year

As a next step, all collected articles were systematically clustered according to the specific focal node, i.e. feedstock, technology, market, and value. The renewable chemical feedstock class defined SCs can only be realised with a focus on optimal combinations of the triplet “feedstock – process technologies – products” (Black, 2016). In addition, the aforementioned triplet has to be coupled with the dimension of commercial “viability” for large scale implementation in order to accomplish the transition from a fossil based economy to an ecological –circular– economy (Paulo, 2013). Therefore, our analysis focuses on the aforementioned four interconnected and mutually interacting nodes of focus.

4. Supply Chain Design Analysis

Based on an extensive synthesis of the literature and our work with leading European Chemicals SC business and academic stakeholders in the context of the EPSRC project “Terpene-based Manufacturing for Sustainable Chemical Feedstocks”, we provide a first generic draft of all the major decisions in designing renewable chemical feedstock based SCs. The inclusive decision-making framework is presented in Table 2. This framework does not present an exhaustive list of all relevant decisions, but rather acts as a synthesis of all decisions that we have identified as part of our on-going research. Below, we briefly discuss the main involved decisions at each focal node. The decision-making process presented clearly documents the multi-dimensional character and complex nature of renewable chemical feedstock based SCs as well as the challenges that have to be addressed for their design and management.

4.1. Renewable chemical feedstock

Renewable chemical feedstocks are regarded as important sources of raw materials that provide the potential to the chemical industry to alleviate the reliance on petroleum, thereby, fostering sustainability. Typical bottlenecks related to the utilization of renewable chemical feedstocks are documented to be: (i) feedstocks' physical and chemical quality attributes (DOE, 2014), (ii) feedstocks' seasonal availability (Castillo-Villar, 2016), and (iii) feedstock supply costs and price variability (Rentizelas, 2009).

Especially, it is strongly supported by existing studies that the increasing trend in the feedstock price dictates the allocation of production/processing facilities closer to the supply sites (Bowling, 2011). The available infrastructure and the feedstock characteristics like geographical locations of sources, pre-processing requirements and regulatory implications also determine the design elements of the entire supply network.

4.2. Technology

Technology can be regarded as the unit operations to extract the desired chemical substrates from the available feedstock. The technological aspect has to be considered across all three SC levels, i.e. upstream (in terms of feedstock volumes from sources to storage facilities and to the pre-processing stage), midstream (in terms of synthesis routes, manufacturing capacity and processing rate), and downstream (spanning from distribution centres to the customer service stations). To that end, candidate locations and infrastructures providing access to the suitable services and utilities, i.e. water and waste treatment, vacant land, and energy supply, should be determined meticulously prior to deploying relevant operations.

Investments comprise a key determinant for the installed capacity and the number of the manufacturing facilities. A major risk factor for the entire supply network is associated with the quality specifications of the sourced feedstocks during the scaling up of processing from the laboratory to an industrial setting (Kenney, 2013). To this effect, processing plant functioning could be associated with considerable economic losses due to large operation and maintenance costs associated with poor feedstock quality and low processing efficiency.

4.3. Market

Potential markets for renewable chemical feedstock based intermediates/end-products are mainly reported to be chemicals (fine chemicals, building blocks, bulk chemicals), organic acids, polymers and resins. A prevalent parameter in the selection of candidate markets is the maturity level or the incipient character of the targeted markets. The great volatility of the chemicals' market in terms of price and demand also highlight the practicality of generating market price/demand scenarios and pursuing contractual prices and demands during the SC planning period (Mansoornejad, 2011).

Table 2 Decision-making framework

	Decision Parameters	References
Renewable Chemical Feedstock	1. Determination of feedstock physical and chemical specifications and quality attributes	Castillo-Villar (2016); Mansoornejad (2010); Melero (2012)
	2. Identification of feedstock seasonal availability patterns	Ekşioğlu (2009); Santibañez-Aguilar (2016); Dansereau (2014)
	3. Identification of feedstock available capacity	Santibañez-Aguilar (2016); Dansereau (2014); Yeh (2015)
	4. Determination of feedstock supply locations	Dansereau (2014); Serrano (2015); Sukumara (2013)
	5. Selection of cost-effective feedstock suppliers	Black (2016); Bowling (2011); Singh (2014)
	6. Determination of feedstock pre-processing requirements, storage and transportation operations	Paulo (2013)
Technology	1. Identification of feedstock conversion technologies and synthesis routes	Castillo-Villar (2016); Melero (2012); Mansoornejad (2010)
	2. Determination of feedstock processing plant locations	Bowling (2011); Ekşioğlu (2009); Singh (2014)
	3. Determination of feedstock processing plant capacity	Ekşioğlu (2009); Gebreslassie (2012); Mansoornejad (2010)
	4. Determination of feedstock processing plant investments	Bowling (2011); Mansoornejad (2011); Singh (2014)
	5. Determination of number of feedstock processing facilities	Ekşioğlu (2009); Gebreslassie (2012); Mansoornejad (2011)
	6. Determination of feedstock processing/production rate	Gebreslassie (2012); Mansoornejad (2010; 2011)
Markets	1. Identification of potential markets	Mansoornejad (2010; 2013); Paulo (2013)
	2. Determination of intermediates/end-product demand	Gebreslassie (2012); Santibañez-Aguilar (2016); Serrano (2015)
	3. Determination of intermediates/end-product price	Bowling (2011); Cambero (2016); Mansoornejad (2010)
Value and Viability	1. Determination of alternative feedstocks	Singh (2014); Xie (2014)
	2. Selection of performance metrics	Mansoornejad (2013)
	3. Selection of partners	Mansoornejad (2011)
	4. Determination of supply chain configuration	Bowling (2011); Ekşioğlu (2009); Xie (2014)
	5. Determination of logistics operations	Ekşioğlu (2009); Xie (2014)

4.4. *Value and Viability*

Circular supply networks arising from renewable chemical feedstock platform technologies can ultimately be treated as product-centric; hence the viability of intermediates and/or end-products based on renewable compounds is an on-going research issue. Technological progress could also reveal the prospects of alternative feedstocks towards: (a) replacement products, (b) substitution products, and (c) novel products. Furthermore, the continuous monitoring and assessment of the financial and environmental performance of the SCs under study is recommended as a proactive action to ensure flexibility towards the rapid regulatory and market advancements at a global scale.

Additionally, a major parameter that impacts the viability of renewable feedstock SCs is the cost of logistics operations. Indicatively, biorefineries are typically located within a 50 miles of radius of the supply sources of biomass. For example, 76% of ethanol in the USA is supplied by small sized biorefineries located in the four major corn producing states in the Midwest (Ekşioğlu, 2009). Moreover, establishing partnerships could leverage external expertise and capabilities in terms of innovative manufacturing, product diversification and delivery, and penetration to new markets. Notably, in volatile markets, network operating policies have to be able to demonstrate a degree of flexibility to produce a portfolio of products in order to ensure SC's margin.

5. Renewable Feedstock Based Circular Supply Chains

In the subsection that follows we present the resulting framework for analysing circular SCs arising from renewable chemical feedstocks. Following, we briefly discuss the building blocks required to determine the viability of the feedstock defined SCs under study.

5.1. Analysis Framework

Today, sustainability goals and drivers are oriented towards the integration of environmental concerns into organisations by minimizing materials' flows or by reducing unintended negative consequences of production and consumption systems (Ilić Nikolić, 2016). To that end, modern SCs need to fulfil market needs under certain commitments like: preserving the environment, offering products of increased value, fostering new economic growth and employment opportunities, and reducing or completely eliminating waste. Therefore, SC management theory has to consider sustainability drivers and goals, and emphasise on the idea of implementing production systems in which materials are reused in an iterative way, in a way to achieve workable relationships between ecological systems and economic growth (Abdul Nasir, 2016), as depicted in Figure 2.

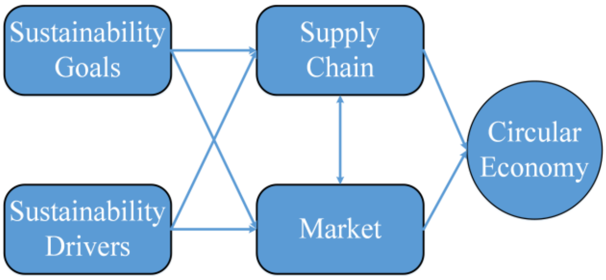
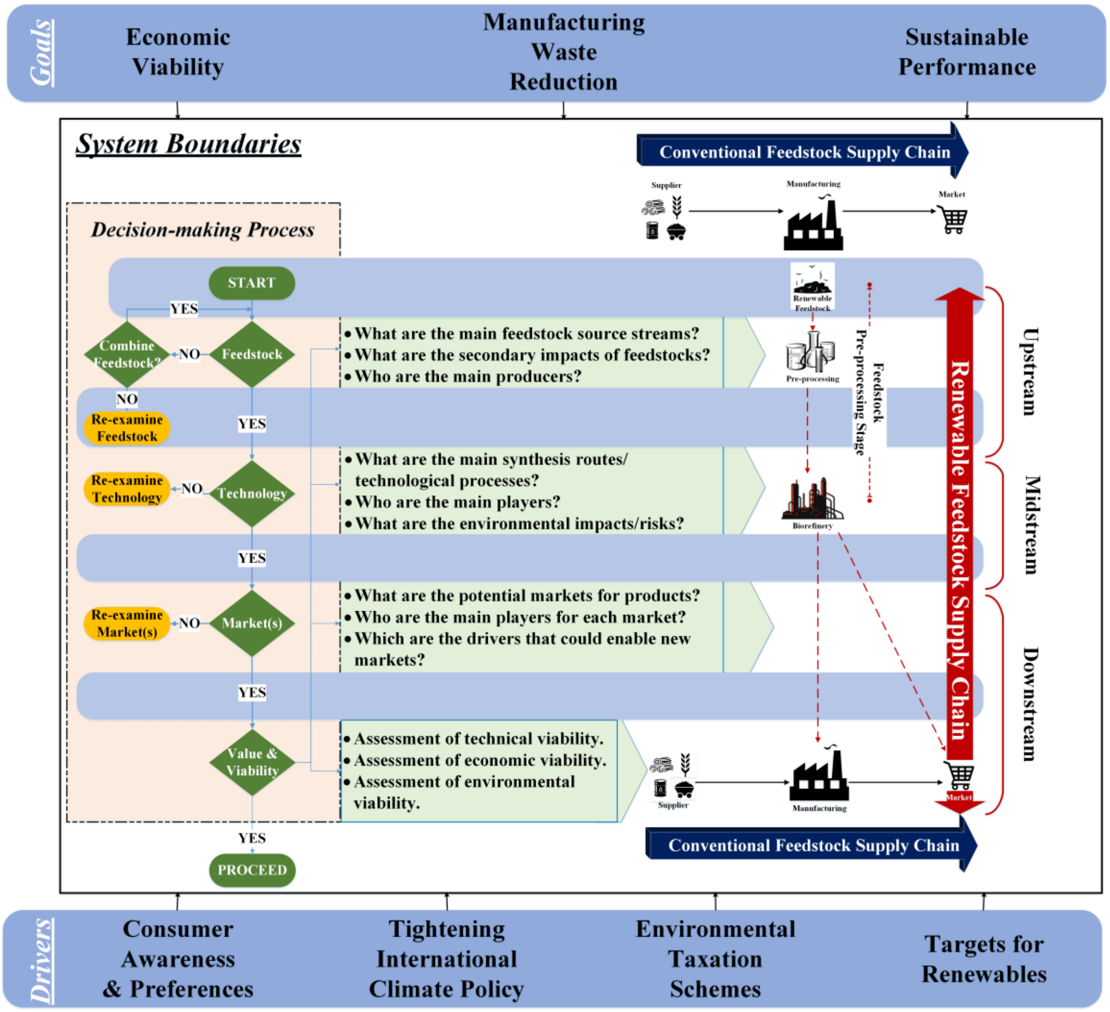


Figure 2 Generic analysis framework for circular supply chains

The proposed decision-making process presented in the previous Section is used to explore SC opportunities emerging from renewable chemical feedstocks and contemporarily to provide a roadmap for designing economically viable supply networks. Following the latter generic analysis outline for circular supply networks, in Figure 3 we present the resulting framework for analysing SCs arising from renewable chemical feedstocks. The network structure is highly influenced by the feedstock specifications and quality attributes, along with the geographical dispersion of the related sources. Furthermore, technology capabilities and market specificities should be meticulously investigated to ensure the viability of the referred SCs.



- What are the main feedstock source streams?
- What are the secondary impacts of feedstocks?
- Who are the main producers?

- What are the main synthesis routes/ technological processes?
- Who are the main players?
- What are the environmental impacts/risks?

- What are the potential markets for products?
- Who are the main players for each market?
- Which are the drivers that could enable new markets?

- Assessment of technical viability.
- Assessment of economic viability.
- Assessment of environmental viability.

Figure 3 Framework for renewable chemical feedstock class based supply chain analysis

5.2. *Viability Assessment Elements*

Literature lacks any ‘one-size-fits-all’ approaches to ensure a balanced evaluation of the economic and environmental performance of a SC, let alone the assessment of its social aspects. Existing quantitative and qualitative valuation approaches rather serve distinct purposes and speak to well-defined specialist domains. The above mentioned gaps are likely to cause misalignment in the way a renewable chemical feedstock is translated into a meaningful object of valuation for different SC practitioners. Hence, we suggest that valuation should be structured according to the essential elements of the renewable chemical feedstock SC at upstream, midstream and downstream levels.

Our decision-making framework further highlights the overarching considerations for assessing the viability of renewable feedstock SCs that include: (i) key technological barriers, (ii) percentage of the original feedstock source that is usefully applied, (iii) stability, transportability and storability of resulting compounds after every processing stage, (iv) transportation and storage costs between stages, and (v) level to which the feedstock is broken down.

Furthermore, our research reveals that the main uncertainties regarding the analysis of renewable feedstock supply networks' viability relates to emissions of feedstock sources (Martire, 2015), cost and manufacturing effectiveness of feedstock processing routes (Ahi and Searcy, 2015), variation of intermediates/end-products (Black, 2016), environmental and financial information (Kremer, 2016), product and market linkages (Luthra, 2016), intermediate products' and feedstock processing steps (Cambero and Sowlati, 2014), and future circular SC governance and relationships (Kulak, 2016).

6. Conclusions

In this study we address the issue of designing circular SCs from source to technology and then market levels. More specifically, we argue from theory that global firms have to explore alternative SC configuration options based on specific renewable chemical feedstocks and tackle a series of key decisions regarding the available feedstocks, the existing technologies and the potential markets of the derived intermediates/end-products.

Furthermore, for designing economically viable SCs we have to acquire and analyse evidence from both qualitative and quantitative data with regards to feedstock quality specifications, geographic allocation of related sources, logistical considerations, storage requirements, process plant locations, synthesis routes and manufacturing capacity, and distribution of intermediates/end-products. The proposed framework aims at capturing the most relevant design variables for the design of viable SCs arising from renewable chemical feedstock platform technologies.

Research in the feedstock SCs is rather extensive, but predominantly focuses on the optimization of operations of individual stakeholders. Therefore, our work aims at streamlining the behaviour of involved stakeholders in a renewable feedstock system as we demonstrate that interactions could drive network viability (Yeh, 2014). Finally, the volatility of renewable feedstocks dictates that the circular SC has to provide a diversified portfolio of added value intermediates/end-products to ensure competitiveness and long-term profitability, whilst safeguarding business operations from seasonal supply or demand cycles and market downturns. We envisage that our framework could assist in effectively determining the portfolio of renewable feedstocks, processing technologies, and intermediates/end-products that provide a balance between profitability in the short-term and value in the long-term during the design and planning phase of a SC. Although our framework has been developed from a compound perspective, it can be used from a process technology perspective as well. In addition, considering that SC assessment comprises an important component in network design and analysis (Beamon, 1998), a set of sustainability performance metrics has also to be proposed.

With regard to future research, we are progressing the current study towards the analysis of terpene based renewable chemical feedstocks as they are essential building-block chemicals for effectively replacing a wide range of petrochemicals and used for the production of added-value derivatives. Indicatively, the Engineering and Physical Sciences Research Council (EPSRC) has recently awarded six research grants through its sustainable chemical feedstocks panel, focusing specifically on renewable chemical feedstocks (Wouter, 2014).

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