Operations Management Research (2018) 11:83–104
https://doi.org/10.1007/s12063-018-0134-y

Mapping supply dynamics in renewable feedstock enabled industries: A systems theory perspective on 'green' pharmaceuticals

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Received: 8 September 2017 / Revised: 28 June 2018 / Accepted: 23 August 2018 / Published online: 8 September 2018

Abstract

This paper provides a multi-stage multi-layer mapping methodology for capturing the macro-level supply chain dynamics that govern industrial systems using renewable feedstocks. The mapping approach combines the Industrial Systems Mapping and System Dynamics principles to systematically capture the interrelations across: (i) institutional players, (ii) sector specialists, (iii) products and intermediates, (iv) production operations, and (v) firms within the supply chain. The interfaces are further explored at four interconnected and mutually interacting theme areas of analysis, namely: (i) renewable chemical feedstocks, (ii) production technologies, (iii) target markets, and (iv) value and economic viability. We demonstrate the applicability of our approach by mapping the dynamics in industrial systems for the production of 'green' pharmaceuticals, particularly via the illustrative case of paracetamol. Through the use of the proposed integrated mapping process the case study demonstrates the principal interrelationships and inter-firm dynamics between the different layers of analysis. Three main drivers are identified that could enhance supply network transformations for improved viability of these developing industrial systems, namely: (i) regulatory conformance with market requirements, (ii) system level feasibility assessment of given renewable feedstocks, and (iii) target market volume demand. The causal feedback elements of the provided mapping technique indicate that it could support the analysis of industrial systems' transformation dynamics enabled by renewable feedstocks. The standardisation of the methodology and its elements provides for an effective visualisation technique with cross-industry relevance.

Keywords Renewable chemical feedstocks · Industrial systems mapping theory · System dynamics theory · Circular economy · Pharmaceutical supply networks · Paracetamol

1 Introduction

In the twenty-first century, the circular economy discourse exerts considerable pressure on the frontiers of manufacturing (Tsolakis et al. 2016), further promoting the notion of sustainability across upstream and downstream operations in industrial supply networks (Zhu and Sarkis 2004). To this effect, traditional manufacturing systems are on the verge of significant transformations (Skellern et al. 2017), especially in light of the potential role of renewable compounds as substitutes to fossil-based raw materials (Behr and Johnen 2009). Consequently, academicians, industrialists and policy-makers need to understand the dynamically evolving industrial landscape stemming from the circular exploitation of renewable feedstocks and embrace the necessary operating model adjustments to craft sustainable and responsive value chain propositions (Porter 1980; Srai and Alinaghian 2013), both at global and local settings. Indicatively, from an environmental standpoint, Huysman et al. (2017) developed a circular performance indicator to assess alternative post-industrial plastic waste treatment management options. The study results reveal that circular alternatives provide an environmental benefit of about 175–355%, in terms of resource consumption, compared to linear economy equivalents. Furthermore, leveraging black solider fly larvae to convert dairy manure and organic waste into high-purity premium-priced protein for livestock feed has major economic and supply network (re)configuration implications (Rehman et al. 2017). In this sense, the conversion of waste into commercially valuable goods, the flexible production scalability and the reduced need for transportation promote decentralised manufacturing networks, as opposed to established centralised global manufacturing hubs and

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distribution operations. Overall, exploring renewable feedstock sources in a circular economy paradigm, while acquiring essential expertise and developing related manufacturing technologies and processing pathways, could ensure competitiveness and economic viability of industrial manufacturing systems (Esfahbodi et al. 2016).

Despite the vivid interest of firms in developing renewable feedstock-based supply chain operations, the ex-ante analysis of related network structures is challenging due to the myopic scope of existing tools and techniques that fail to capture the varying levels of dynamism and complexity in industries (Nair and Boulton 2008). In principal, existing supply chain mapping tools and decision-making frameworks are linear in nature (Joubioux and Vanpoucke 2016). In this regard, they fail to capture any evolution pathways, along with the underpinning causalities, which are essential for conceptualising industrial-level transformations (Cagliano et al. 2008), predominantly in relation to institutional developments and technology advances. Moreover, the extant mapping tools often seem to neglect the triplet “people-process-product” thus limiting management’s ability to proactively inform about alternative firm strategy options, data flow processes, system stability and complexity phenomena; hence, making reliable inferences about future states of industrial supply networks is challenging (Forno et al. 2014). Characteristically, the mapping methodology provided by Srai et al. (2016) sets out the basics for consistently mapping industrial systems, but it is rather static in nature in the sense that the presented mapping technique does not capture the dynamic interrelations among key stakeholders and relevant product and process entities at each supply chain echelon.

In order to explore sustainability-focused advancements in industrial supply networks, and further support the competitiveness and commercial viability of manufacturing activities, the operations research community needs to provide appropriate systems’ mapping methodologies. In conjunction with consistent data collection methods, the mapping tools could facilitate the process of systematically capturing and visualising the underlined macro, meso and micro-level system interactions (Srai 2017). However, existing mapping tools need to be validated, tested and refined through specific industrial case studies. Additionally, the existing mapping tools’ linear structure is a major drawback that often limits the capability to capture underpinning evolution pathways and causal effects which are essential for conceptualising industry transformations associated with institutional and technology developments. In particular, the circular economy discourse dictates that industrial ecosystems consider a symbiosis of a plethora of business actors, institutional stakeholders and relevant product and process entities whose dynamic interrelations impact the sustainability efficiency of manufacturing systems (Herczeg et al. 2018). To that end, a mapping approach incorporating structural elements of the System Dynamics theory could assist in effectively capturing the plethora of causal effects and feedback dynamics in supply networks (Homer and Oliva 2001; Williams et al. 2003). The System Dynamics methodology has a proven track record for tackling strategic decision-making problems as it adopts a top-down approach and can assist in capturing the complex nature and dynamic impact of on-going developments in the supply, technology and market fronts of an industrial manufacturing system (Tsolakis and Srai 2017). Therefore, a System Dynamics-based mapping technique can inform managers, industrialists and policy-makers about the governing dynamics associated with the exploitation of renewable feedstocks in industrial systems, along with technological advancements and market characteristics, in order to proactively evaluate network transformations and (re)configurations in terms of sustainability and economic viability.

In this work, a methodology for mapping and visualising industrial systems stemming from the utilisation of renewable chemical feedstocks, following a supply chain perspective, is developed to address an evident gap in the current theory and practise. More specifically, a multi-stage multi-layer mapping approach for industrial systems enabled by renewable chemical compounds is developed in order to better understand the dynamic relationships and interactions among the involved institutional, industrial and supply chain stakeholders, along with the related product and process entities. The provided methodology is based upon the Industrial Systems Mapping theory, combining structural elements of the System Dynamics theory, so as to enable the capturing of industry specific high-level dynamics and (re)configuration phenomena (Kristianto et al. 2012). The contribution of the proposed mapping technique refers to the inherent feedback loops that differentiate it from existing mapping approaches. The underpinning causality mechanism allows stakeholders to map dynamic phenomena in a system under study and inspires future scenario planning. We discuss the applicability of the proposed approach via the analysis and design of pharmaceutical supply network systems arising from renewable chemical feedstock compounds, specifically focusing on the illustrative case of ‘green’ paracetamol. The elaborated approach further reveals critical factors that drive network transformations and commercial viability of alternative renewable chemical feedstock-based product offerings.

This research is based on the premise that a circular paradigm is important for the sustainable and viable development of industrial manufacturing operations; however, transformations of existing networks are required to be assessed (Zeng et al. 2017). In this regard, this research study investigates industrial supply networks that could utilise renewable feedstocks in an attempt to tackle the following research questions (RQs):

- RQ#1: Are current industrial systems’ mapping methodologies sufficient to describe the evolution of industrial supply networks within a circular economy?

- RQ#2: Which structural elements are important in capturing the circular nature of renewable feedstocks when mapping industrial systems?
- RQ#3: Which are the main drivers that could foster transformations and supply chain (re)configuration options for competitive and commercially viable manufacturing networks enabled by renewable feedstocks?

These articulated RQs are critical to be answered to promote improvements on existing mapping approaches by accommodating renewables and exploring their impact dynamics in industrial supply networks. A real-world example further motivates the potential use or renewable compounds in the pharmaceutical industry and communicates potential supply network transformations. More specifically, gaps identified in the extant literature will answer RQ#1. Following that, the answer to RQ#2 will recognise key mapping elements that should be considered when capturing circular supply chain dynamics in industrial systems arising from renewable feedstocks. The proposed mapping methodology – defined by the answer to RQ#2 – is demonstrated through its application on the real-world case of a common medication and returns important insights about the utilisation of renewable chemical feedstocks in the pharmaceutical industry. Finally, the answer to RQ#3 identifies the key drivers for (re)configuring industrial supply network systems using renewable feedstocks for ensuring economic viability.

This paper follows a multi-method approach to address the enunciated research queries. More specifically, literature findings are utilised to identify key industrial systems mapping studies to answer RQ#1. Furthermore, a synthesis of theoretical constructs and mapping techniques along with experts' opinions results in a mapping framework thus answering RQ#2. The case study analysis demonstrates the integrated mapping methodology, returns useful insights and reveals future research avenues, hence further assisting in tackling RQ#2. Finally, the critical literature analysis in conjunction with empirical evidence and business and research expertise is utilised for answering RQ#3.

The remainder of this paper is structured as follows: Section 2 sets out the materials and methods that underpin the present research. Following that, a critical taxonomy of the extant literature on supply chain systems' mapping is inserted in Section 3. Then, Section 4, based on the literature findings, sets out a proposed mapping framework for industrial manufacturing systems enabled by renewable chemical feedstocks. Section 5 tests the advised mapping framework on an illustrative pharmaceutical industrial system, from a supply chain angle. The study results along with the integrated mapping approach and key transformation drivers are presented in Section 6. Finally, we wrap up with discussion, conclusions, limitations and future research perspectives in Section 7.

2 Materials and methods

In order to develop a coherent conceptual structure of a topic, the object of scrutiny has to be a synthesis of the extant literature (Tranfield et al. 2003). Thereafter, primary research is pivotal so as to validate the theoretical constructs, draw causal inferences and make recommendations for the management practise (Scandura and Williams 2000). The basic terminology, theoretical lens, and empirical research relevant to this research study are stipulated in the following sub-sections.

2.1 Basic terminology

Considering that the focus of this research is mapping industrial systems enabled by renewable feedstocks, it is necessary to define the terms 'industrial system map' and 'enabling [technology]' in this context. As 'renewable feedstock' we identify any biological or non-biological material that, under certain processing stages, can be converted to another form of intermediate and/or end-product that can be used as value-added input to manufacturing operations.

Firstly, industrial system maps are tools which are used to capture key elements for a range of industrial supply networks and explore the underlining relationships that define networks' performance and progressive evolution. More specifically, in this study we adopt the view provided by Srai and Gregory (2008) who describe supply network configuration maps as a useful mechanism for capturing and visually representing supply network configurations for further allowing a consistent and coherent analysis. Notably, supply chain maps need to capture the following elements: (i) network shape and structure, (ii) ownership, (iii) levels of vertical and horizontal integration, (iv) relationships and inter-dependencies between network partners, (v) unit operations, (vi) product offerings, (vii) infrastructure, and (viii) network dynamics.

Secondly, considering the inherent dynamism encapsulated to the aforementioned industrial systems' mapping elements, along with our aim to understand network (re)configuration dynamics stemming from the utilisation of renewable feedstocks in manufacturing, we adopt the view of Zhang et al. (2012) who define enabling technologies in the bio-based economy as: "*... technologies for efficient utilization of inexpensive and renewable resources for the production of target compounds.*". Enabling technologies can have quite massive spillover effects via driving technological change and influencing business models (Teece 2018).

2.2 Theoretical lens

The present research work shares the systems view of the Supply Chain and Operations Management domain, with research focus being on discovering cause-and-effect relationships within an objective reality (Gold 2014). Complementarily, the ability to capture and analyse the development of industrial supply chains over time generally supports the apprehension of operating model amendments to leverage subsequent growth opportunities and support future evolution pathways in operations management (Srai 2017). In this regard, we leverage the System Dynamics theory proposed by Forrester (1961) to map complex systems while further capturing the causalities that define the dynamic behaviour of the industrial networks of interest. In supply chains, System Dynamics allows the capturing of the relationships among the involved network stakeholders and product and process entities, from an end-to-end standpoint, to understand and assess systems' behaviour over time (Saavedra et al. 2018). System Dynamics also allows for the development of representative simulation modelling tools that facilitate the quantitative analysis of complex systems' behaviour over the course of time. The feedback control characteristics of System Dynamics along with the associated causal loop diagrams and stock and flow maps render the approach as an appropriate methodology for decision-making at the strategic level (Tsolakis and Anthopoulos 2015), applicable to a wide range of managerial, socioeconomic and organisational cases (Sterman 2000). Typically, a causal loop diagram uses directed arrows to represent the relations between dependent (i.e. cause) and independent (i.e. effect) variables in a system, while a polarity is also assigned at each arrow. A positive (+) polarity denotes that the effect changes towards the same direction as the cause (reinforcing feedback, R). On the other hand, a negative (−) polarity denotes that the effect changes towards the opposite direction of the cause (balancing feedback, B).

To enable a more detailed analysis, the approach elaborated in this study embraces the mapping framework proposed by Srai (2017) and Srai and Christodoulou (2014). In this regard, our mapping activity includes five stages of stakeholders and product and process related entities, capturing: (i) institutional players, (ii) sector specialists, (iii) products and intermediates, (iv) production operations, and (v) firms within the supply chain. An industrial systems' mapping methodology should be able to inform about the role of institutional, regulatory and technological advancements in the manufacturing sectors through (Harrington and Srai 2012):

- capturing the industry structure and system's interrelations at a high level,
- identifying evolutionary phases of the supply chains within the industry, and
- enabling the generation of supply chain future transformation models, from the involved actors' perspective.

Then, business stakeholders could compare current states and possible future scenarios of already deployed industrial manufacturing systems to further outline interventions and (re)configuration policies to support competitive transformations in industries.

In addition, considering upcoming advances that could shape industrial manufacturing systems in a circular supply chain context, enabled by the utilisation of renewable feedstocks, the mapping process presented in this study encapsulates four essential theme areas (Tsolakis et al. 2016), including: (i) renewable chemical feedstocks, (ii), production processes and technologies utilised to manufacture value-added intermediates and/or end-products, (iii) market and institutional arrangements, and (iv) value and commercial viability constituents. The aforementioned four theme areas are confirmed as essential for exploring emerging (re)configuration opportunities for supply chains enabled by renewable feedstocks (Srai et al. 2018). In particular, Srai et al. (2018) provide a comprehensive decision-making process and a concise framework for exploring commercially viable supply chain configurations arising from renewable feedstocks, towards delivering value-added intermediates and/or end-products in a circular economy context. Empirical evidence from primary industries, such as chemicals and pharmaceuticals, demonstrate the necessity to tackle a series of key-decisions in these four theme areas for the systematic analysis, both qualitative and quantitative, and design of renewable feedstock-based supply chains (Tsolakis et al. 2016; Kawaguchi et al. 2016). Whereas the primary analysis of traditional networks revolves around a specific product or a firm, supply chains that use renewable feedstocks have to be primarily analysed from a compound-level (Böhmer et al. 2012; Srai et al. 2018), e.g. feedstock availability, quality specifications, physicochemical properties. Following that, synthesis pathways and technology options determine upscaling production opportunities for the resulting intermediates and/or end-products (Xu et al. 2012), along with any possible by-products. At a third stage, investigation of established or new markets for the derived goods, either as substitutes or novel offerings, can dictate any product supply chain (re)configuration options (Black et al. 2016). Finally, the integration of the previous elements leads to the evaluation of the elaborated renewable feedstocks' economic viability (Paulo et al. 2013).

To sum up, our proposed mapping methodology uses the System Dynamics approach to map five categories of stakeholders and product and process related entities (i.e. institutional players, sector specialists, products and intermediates, production operations, firms) at each of the four identified theme areas (i.e. renewable feedstock, technology, market, value and viability). Thus far, the understanding and analytical capability on industrial and supply network evolution, especially for the domain of renewable feedstocks, is rather limited (MacCarthy et al. 2016). In this regard, we suggest that the mapping of key stakeholders and product/processes entities at each of the 'feedstock-technology-market-value and viability' theme areas allows for the consistent analysis and improved understanding of enablers in renewable feedstock-based supply chains, in a repeatable manner.

2.3 Empirical research

The development of the analysis framework and the integrated mapping approach for the study of renewable feedstock-based supply chains is theoretically grounded on a fourfold nexus of theme areas, as described in subsection 2.2. The proposed mapping methodology, further detailed in Srai et al. (2018), is underpinned by literature evidence and fourteen interviews with industry experts and academics alike who have a long-term involvement in the field of renewable chemical materials. The informants' specialisation refers to: (i) renewable chemical feedstocks – three experts, (ii) chemical engineering – four experts, (iii) chemistry – three experts, (iv) biology and biochemistry – one expert, (v) pharmaceuticals – one expert, and (vi) systems engineering – two experts. Following that, a multi-stakeholder workshop was organised to collectively refine the literature and empirical outputs and validate the proposed mapping approach.

The mapping framework and the integrated mapping approach for the investigation of the specified pharmaceutical case are based on our collaboration with leading European chemical supply chain businesses and academic stakeholders in the context of the Engineering and Physical Sciences Research Council (EPSRC) funded project "Terpene-based Manufacturing for Sustainable Chemical Feedstocks" (EPSRC Reference: EP/K014889/1). The project consortium recognises System Dynamics as a valuable methodology for: (i) mapping pharmaceutical industrial systems, (ii) comprehending the systems' evolving dynamics at a strategic setting, and (iii) advancing network (re)configuration theories in the pharmaceutical supply chains' field.

3 Industrial systems mapping: A critical taxonomy

Mapping approaches are mainly used in the existing body of literature to visualise end-to-end supply networks (Phaal et al. 2011). A key challenge that nascent and evolving industries are confronting, like for example 'green' pharmaceuticals (Tsolakis and Srai 2017), associates with the lack of defined strategies that a firm could pursue in order to effectively respond to the gamut of potential complexities and uncertainties stemming from foreseen market opportunities. To that end, value network and supply chain (re)configuration mapping approaches might enhance the derived insights about the interactions among different stakeholders and echelons at manufacturing value chains; hence, the development of appropriate supply chain adaptation and (re)configuration strategies is allowed. Thereafter, supply networks could act as a supporting element of industrial evolution (Srai and Gregory 2008; Srai 2010). Following a supply chain perspective, Srai (2017) documents the main attributes of industrial systems' mapping techniques to be: (i) flows (i.e. financial, information, material), (ii) value-added activities, (iii) network structure and boundaries, (iv) geographical dispersion of operations, (v) relationships between actors, and (vi) product scope and life cycle.

In the extant literature, preliminary industrial ecosystem maps were developed by Padrón Castro (2013) and were further classified according to four sections, namely: (i) institutional actors, (ii) value chain actors, (iii) industrial actors, and (iv) technology. Srai (2017) develops an integrated mapping approach combining industrial system actors and supply chain configuration analyses to explore the characteristics of developing industries in the United Kingdom, specifically focusing on the industrial biotechnology and photovoltaics industries. In the same vein, Srai et al. (2016) use an industrial systems' mapping methodology to capture the interdependencies among institutional and industrial actors to analyse the redistribution potential in six emerging industries, namely: aerospace, maritime, built, biotechnology, photovoltaics and last mile logistics.

Furthermore, Tyagi et al. (2015) use the value stream mapping technique to determine the current state of the product development process in a gas turbine manufacturer with the aim to identify waste streams in the manufacturing process and outline an action plan for eliminating waste generation in a future state. Nuss et al. (2016) describe the supply chain mapping of five technology platforms consisting of potentially critical metals to identify network stakeholders that might act as potential 'hotspots' in terms of substitutability, environmental sustainability, and resources' availability. Windisch et al. (2013) present a mapping framework for business processes in Finish and German wood supply networks. In addition, Srai and Gregory (2008) develop a mapping approach that links supply chain configuration to intrinsic network capability and performance, thus allowing for the re-evaluation of operational process excellence models. Dagnall et al. (2000) use resource mapping to determine the locations of collectable farmyard manure and anaerobic digestion plants across the United Kingdom and explore opportunities for potential biomass-to-energy schemes.

Related to the industrial systems' analysis, mapping techniques are often elaborated in the extant literature for the planning of investments and business development. For example, De Propris (2005) provides a three-level diagnostic analysis procedure for mapping local production systems in the United Kingdom based on: (i) spatial analysis, (ii) inter-firm relationships' analysis, and (iii) local and regional institutional framework analysis. In a similar context, Lazzeretti et al. (2008) map the creative local production systems in Italy and Spain to motivate authorities towards supporting policies that could foster the geographical dispersion of industrial clusters. Mapping techniques have also been proposed for consulting the proper planning of industrial growth centres with refer to the regional proneness towards natural and technological hazards (Gupta et al. 2002).

A taxonomy of the literature on mapping industrial systems and value networks, according to the objective and the type of analysis, is provided in Table 1. Notably, Table 1 critically assigns the reviewed studies on the four theme areas recognised by Tsolakis et al. (2016) as essential for investigating supply chain (re)configuration options stemming from the utilisation of renewable feedstocks. This critical taxonomy reveals the myopic focus of the extant mapping approaches. Moreover, key limitations of the reviewed mapping studies are identified, further highlighting their unanimous negligence of causal loop feedback mechanisms.

Above all, our critical taxonomy primarily demonstrates the lack of research efforts, on the industrial systems' mapping field, that capture cause-and-effect relationships among the involved stakeholders and product and process entities involved in the five stages proposed by Srai (2017) and Srai and Christodoulou (2014). Mainly, the literature findings reveal that existing relationships among different stakeholders and entities, across the five abstraction stages, are captured in a linear and static perspective. In principal, the latter finding is in contrast to the definition of industrial systems' mapping process that specifically outlines the capturing of the dynamics among supply network systems' elements, from a multi-stage perspective. Furthermore, although mapping key stakeholders and activities is essential for recognising transforming (re)configuration dynamics, the vast majority of existing studies fails to specify, or even identify, such key product and process entities. In this respect, the integration of the relevant System Dynamics structural elements into a comprehensive industrial system's mapping methodology could assist in strategically identifying supply network systems' (re)configuration opportunities in order to exploit renewable feedstocks, thus possibly fostering the sustainability of all stakeholders.

4 Renewable feedstock-based supply networks: A mapping framework

Considering that alternative supply chain configuration options entail stakeholders across spatial and temporal constituents, we suggest that for the effective mapping of supply chains that exploit sustainable feedstocks in a circular economy context the elaborated approach should comprise of four well-established theme areas of analysis (Srai et al. 2018), which could be applied in a stepwise sequential process, namely: (i) renewable chemical feedstocks, (ii) production technologies, (iii) target markets, and (iv) value and economic viability. Figure 1 depicts the proposed methodological framework for particularly guiding the mapping of industrial supply network systems enabled by renewable chemical feedstocks. The framework builds upon five stages of stakeholders and product and process entities whose concise mapping is required to validate and verify any conceived (re)configuration options at each of the abovementioned theme areas of analysis. According to Srai (2017) and Srai and Christodoulou (2014), the mapping elements at each stage that further guide the data gathering process, include: (i) institutional players and secondary stakeholders (key entity - A1), (ii) sector specialists and primary stakeholders (key entity - A2), (iii) core products (key entity - A3), (iv) core processes (key entity - A4), and (v) core firms (key entity - A5). The mapping sufficiency is evaluated on a five-scale level, namely: (i) sufficient, (ii) somewhat sufficient, (iii) neither sufficient nor insufficient, (iv) somewhat sufficient, and (v) insufficient. As we progress with the implementation of the framework downstream at theme area level, the mapping sufficiency requirements increase along with the added value at each stage. Useful information and insights are gained at the renewable feedstock analysis phase as the involved complexity is limited. Progression to the subsequent theme areas of the framework is feasible only in case the mapping results are validated and verified, while different aspects of the key identified entities are investigated.

5 Pharmaceutical industrial systems' mapping: An illustrative case

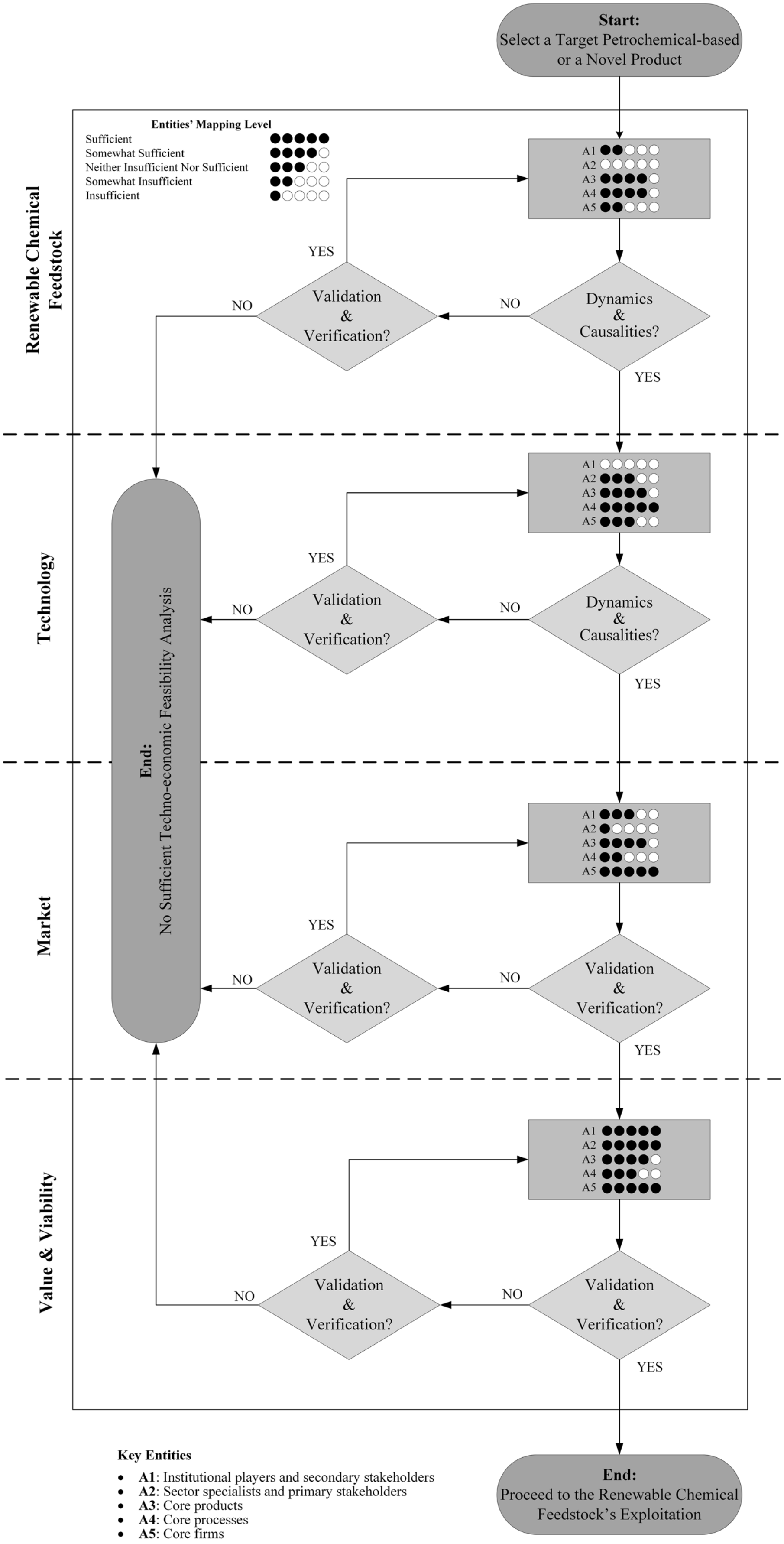
Pharmaceutical manufacturing is a prominent industrial case characterised by evolving dynamics both upstream (i.e. supply) and downstream (i.e. distribution and healthcare delivery), thus providing grounds for advancements in theory and practice (Settanni et al. 2017). The need to consistently map the industrial landscape in the pharmaceutical sector and understand the dynamics in the corresponding supply networks is thus evident. Particularly, comprehending the future macro, meso and micro-level structure of pharmaceutical industrial systems assists in identifying the evolving challenges that could impact the performance of the relevant sectoral and national economies (Srai and Alinaghian 2013; Saikia 2014).

In particular, 'greener' manufacturing interventions are becoming a valuable capability for pharmaceutical supply networks (Srai et al. 2015). Notably, the United Nations and specifically the Millennium Development Goals Target 8.E prompts the pharmaceutical industry to provide patients with equitable access to essential medicines which are

Table 1 Taxonomy of selected industrial systems' mapping studies

Reference	Objective	Type of Analysis	Theme Area	Key Mapping Limitations
Dagnall et al. (2000)	Feedstock sources identification	Resource mapping	Feedstock	• No causalities are captured • No end-to-end stakeholders are identified • Scope is limited to local bioenergy systems
De Propris (2005)	Intervention policy measures' formulation	Firms' agglomerations' diagnostic analysis	Value & Viability	• No causalities are captured • No end-to-end stakeholders are specified • Scope is limited to local production systems
Gupta et al. (2002)	Planning industrial growth centres' development	Environmental risk mapping	Value & Viability	• No causalities are captured • No end-to-end stakeholders are considered • Scope is limited to environmental risks
Lazzeretti et al. (2008)	Intervention policy measures' formulation	Firms' clusters' analysis	Value & Viability	• No causalities are captured • No end-to-end stakeholders are specified • Scope is limited to local production systems
Nuss et al. (2016)	Supply chain risk identification	Supply chain network analysis	Technology	• No causalities are captured • No end-to-end stakeholders are considered • Scope is limited to product platform risks
Srai (2017)	Enabling technologies, processes and actors' identification	Supply chain network and institutional actors' analysis	Technology	• No causalities are captured
Srai and Gregory (2008)	Supply network design	Supply network configuration	Value & Viability	• No causalities are captured
Srai et al. (2016)	Redistribution manufacturing potential identification	Value chain mapping	Value & Viability	• No causalities are captured
Tyagi et al. (2015)	Product development	Value stream mapping	Value & Viability	• No causalities are captured • No end-to-end stakeholders are considered • Scope is limited to waste minimisation • Primary, subjective research is required
Windisch et al. (2013)	Business processes and stakeholders' identification	Business process mapping	Technology	• No causalities are captured • Scope is limited to supply chain processes

Fig. 1 Mapping framework for supply networks enabled by renewable chemical feedstocks



clinically efficient, environmental friendly and cost-effective (United Nations 2015). Following that, the environmental performance of national healthcare systems could also be improved (Leder et al. 2015) contemplating that they set significant procurement orders for pharmaceuticals (Ryan-Fogarty et al. 2016), at a global scale. Therefore, the evaluation of 'greener' manufacturing interventions along with the related supply chain (re)configuration opportunities are becoming a valuable capability for the pharmaceutical sector (Srai et al. 2015; Tsolakis et al. 2016).

The mapping methodology proposed in this research is applied on pharmaceutical industrial systems as the respective manufacturing operations support both global and regional economies. However, digitalisation and circular economy ramifications, along with institutional and societal arrangements, could provoke major disruptions in pharmaceutical industrial systems in terms of delivering consumer-centric sustainable solutions. Indicatively, pharmaceutical firms in India are documented to face discontinuous institutional changes in their domestic environment due to economic liberalisation, sustainability concerns and intellectual property reforms (Chittoor et al. 2009). In addition, a challenge that is often neglected relates to the continuously improving living standards, mainly in low and middle-income countries, that associates to the emergence of non-communicable diseases and the subsequent amplified demand for access to modern healthcare services and pharmaceuticals. Therefore, challenges and opportunities for pharmaceutical industrial systems are being crafted with further implications on the societal cohesion and prosperity. Additionally, the pharmaceutical sector conforms to the criteria suggested by Srai (2017), namely:

- defined by technology/process platforms,
- governed by strict international regulations and rapid technology/process advancements,
- fragmented by patents and particular key suppliers that imply alternative mapping opportunities especially for the cases in which patents expire,
- exposed to supply chain risks thus necessitating the prescriptive investigation of mitigation strategies, and
- servicing multiple classes of users often requiring personalised solutions.

Considering the industrial evolutionary phenomena stemming from renewable chemical feedstocks-driven manufacturing operations, the industrial evolution process is not linear but is rather underpinned by a plethora of complex iterations and interactions among different elements and factors (Schmoch 2007).

Motivated by recent advancements in 'green' manufacturing, an illustrative case used to exemplify our proposed mapping methodology is paracetamol. Paracetamol (also known as acetaminophen) is an active pharmaceutical ingredient (API) which is used to manufacture non-steroidal analgesics. The global consumption of paracetamol is estimated to be around 140 k tons per annum with a projected market value of over USD1.0 billion or about 201.2 k tons in terms of volume by the year 2022 (Transparency Market Research 2015). From an industrial system's perspective, the presence of advanced manufacturing facilities, cheap and abundant labour, developed infrastructure, availability of a wide range of raw materials and intermediate products is driving paracetamol production in Asia Pacific countries. Overall, manufacturers located in China and India produce about 70% of the globally available paracetamol, on an annual basis.

Within the scope of the "Terpene-based Manufacturing for Sustainable Chemical Feedstocks" research project, novel catalytic conditions to develop a sustainable and scalable catalytic flow-synthesis of 'green' paracetamol based on renewable chemical feedstocks are explored. 'Green' paracetamol will be used as a showcase to the wider business community of the untapped potential of using inexpensive terpenoid feedstocks as precursors for the sustainable synthesis of pharmaceuticals. Terpenes consist a large and diverse class of organic compounds, widely distributed in plants, which can be readily upgraded using existing petrochemical technologies to derive value-added chemicals for the pharmaceutical, biotechnology, food and cosmetics industries (Augustin et al. 2011; Thimmappa et al. 2014). Therefore, to ensure market value and economic viability, the assessment of potential evolution pathways for terpene-based manufacturing along with the development of industrial and supply network maps is required. Such evaluations can then inform appropriate (re)configurations in the related industrial systems and supply networks.

A typical pharmaceutical supply system includes the following echelons of network operations: (i) chemical feedstock supply for the synthesis of the targeted API and excipients, (ii) primary manufacturing where the raw materials are processed into the needed API, (iii) secondary processing where the API is manufactured into the desired pharmaceuticals' dosage forms, (iv) packaging where the units of dosage forms are manufactured into packages to be dispensed to the market, and (v) retailing where demand is defined based on the consumers' needs. As consumers are identified both the individual patients who might be environmental conscious and the national healthcare systems that are obliged by international regulations to procure sustainable medications. A generic pharmaceutical supply system is illustrated in Fig. 2 that further indicates alternative supply chain (re)configuration opportunities arising from renewable chemical feedstocks. It is noteworthy to clarify that our

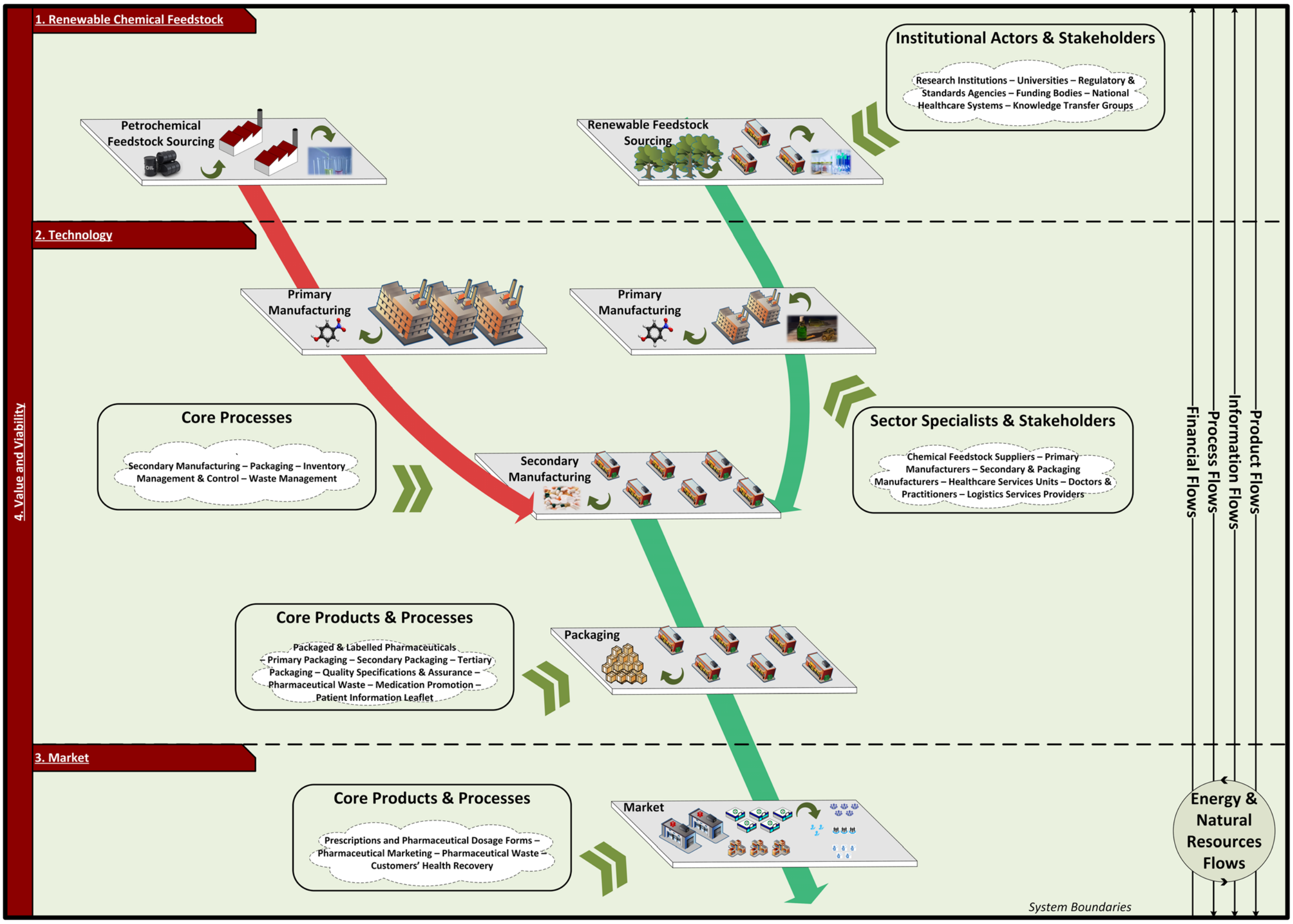


Fig. 2 Structure of pharmaceutical supply networks and (re)configuration opportunities enabled by renewable chemical feedstocks

mapping approach does not extend to the research and development phases of 'green' and/or 'bio' pharmaceuticals but rather focuses on the (re)configuration opportunities stemming from the use of renewable chemical feedstocks in manufacturing operations.

Below, we schematically present the proposed mapping approach, at each of the four identified theme areas of analysis, specifically developed for pharmaceutical industrial systems. In particular, to capture the dynamic interrelations that promote transformations and (re)configurations in the sector, our analysis is based on the System Dynamics principles to stress the cause-and-effect relations among the five-stage stakeholders and product and process entities, as these are mapped at each theme area. Considering the macroscopic view of the provided mapping approach, the directed arrow connections represent product, information and monetary flows, without providing any indication about the flows' scale of magnitude. The proposed System Dynamics mapping approaches were examined regarding their structural validity according to Sterman (2000), including: (i) rational interpretation of the mapped interrelations, (ii) analysis and understanding of the relevant literature evidence, and (iii) capture and interpretation of experts' inputs captured during the organised interviews and workshop. The structure of all feedback loops, per theme area of analysis, is presented in Appendix 1 Table 2.

5.1 Renewable chemical feedstock

Generally, pharmaceuticals are manufactured through complex chemical processes that utilise petrochemical-based feedstocks as raw materials. However, a number of recent research initiatives emphasises the transition from fossil-based feedstocks to renewable alternatives. Therefore, prior to the API formulation, a fundamental step is the identification of renewable chemical feedstocks that conform to specific technical, quality and economic feasibility standards that facilitate their further exploitation for manufacturing pharmaceuticals at an industrial scale. Indicatively, the API for 'green' pharmaceuticals could be synthesised from terpenoid feedstocks available in the flora or extracted from compounds present in industrial waste (Tsolakis et al. 2016). Following the feedstock focus strand, specialist suppliers procure the appropriate raw materials required by primary manufacturers. Typically, such key suppliers have a limited supply capacity, are geographically scattered across the globe and are vulnerable to risks hence impacting the resilience of the entire supply chain. To that end, research initiatives and business stakeholders demonstrate a vivid interest on the exploration of a range of diversified chemical feedstocks for producing similar APIs. In this sense, the use of renewable feedstocks can lead to resilient supply networks in terms of upcoming increased market needs, while they can assist in developing a risk mitigation capacity to effectively adapt to the on-going pharmaceutical landscape metabolisms.

For the exemplar case of paracetamol, the industrial formulation of the API is typically based on petrochemical feedstocks like phenol or p-nitrochlorobenzene sourced from specialist chemical industries/laboratories located mainly in China or India (Settanni et al. 2016). For the 'green' paracetamol case investigated in our participating project we find that the API could be manufactured from terpenoid feedstocks, either limonene or β-pinene. The identification of suppliers of limonene – found in significant concentrations in citrus waste – or β-pinene – extracted in substantial volumes from crude sulphate turpentine found in waste from kraft paper and pulp industries – is essential for: (i) ensuring adequate supply of renewable chemical feedstock volumes to the API manufacturing firms, and (ii) assuring a reasonable procurement pricing strategy.

The complexity and non-linear behaviour in the 'Renewable Chemical Feedstock' theme area is captured through the identification of feedback loops. Indicatively, in the balancing loop B1, an increase in the number of '*Chemical Feedstock Quality Standards*' imposes constraints that limit the '*Chemical Feedstock Suppliers' Number*' which in turn decreases the available '*Chemical Feedstock Installed Capacity*'. Decreased feedstock installed capacity entails limited '*Chemical Feedstock Supply*', resulting in an increase in '*Chemical Feedstock Price*' and thus limiting the renewable '*Chemical Feedstock Demand*'. In response to the resulting lower demand, '*Chemical Feedstock Quality Standards*' in generic applications are lessened to motivate utilisation of renewable feedstocks in industrial applications. The causal loop diagram that captures the mental model of the feedstock theme area which managers could conceive is depicted in Fig. 3.

5.2 Technology

A significant aspect of mapping approaches in the technology theme area of analysis relates to the demonstration of the way that alternative manufacturing processes result in different value-added intermediates and/or end-products (Srai 2017). Particularly, in pharmaceutical industrial systems technology should be considered across the following echelons, namely:

i. primary manufacturing to synthesise the targeted API,
ii. secondary manufacturing to produce the desired dosage forms of pharmaceuticals, and
iii. packaging to combine packaging, serialisation, artwork and labelling functions aiming to ensure product safety and prevent patient misuse.

The aforementioned three supply chain echelons of operations are valid for the industrial production of the majority of medications, following the research and development and clinical trial strands. Therefore, in the technology theme area any technological innovations or advancements in chemical synthesis pathways are expected to have an impact on the unit operations level, further determining the performance of the entire pharmaceutical supply network.

Based on the specific case of 'green' paracetamol that we discuss, the selection of renewable chemical feedstocks as opposed to petrochemical alternatives for manufacturing the desired API has major repercussions in terms of synthesis routes and required infrastructure. Currently, paracetamol manufacturing is based on iron reduction as opposed to the 'green' chemistry route referring to the direct amination of hydroquinone (Joncour et al. 2014). Within the context of the participating project, the elaboration of either limonene or β-pinene as renewable feedstocks to provide the targeted API is associated with different production inputs and equipment, cost elements and resulting by-products. In addition, a prominent trend at the technology theme area is the shift towards continuous as opposed to batch manufacturing of APIs.

Following the primary manufacturing stage, pharmaceutical dosage forms are produced at the secondary manufacturing echelon (Meneghetti et al. 2016). Dosage forms may include tablets, capsules, suppositories, inhalers, powders or any other form. Nowadays, digital manufacturing technologies and especially 3-D printing are already applied for the manufacturing of pharmaceuticals' dosage forms aiming to increase inventory control efficiency, ensure market responsiveness and provide personalised medications according to patients' health profile and related needs (Srai et al. 2014).

Thereafter, medication packages are produced and distributed to the market. Advancements in the field refer to 'smart' packages and the exploitation of radio-frequency identification tags to monitor storage conditions and enhance the visibility across the pharmaceutical supply chain.

Prior to the diffusion of the aforementioned advancements in the technology theme area, technoeconomic feasibility is required to be ensured by the responsible research and development institutions following the support

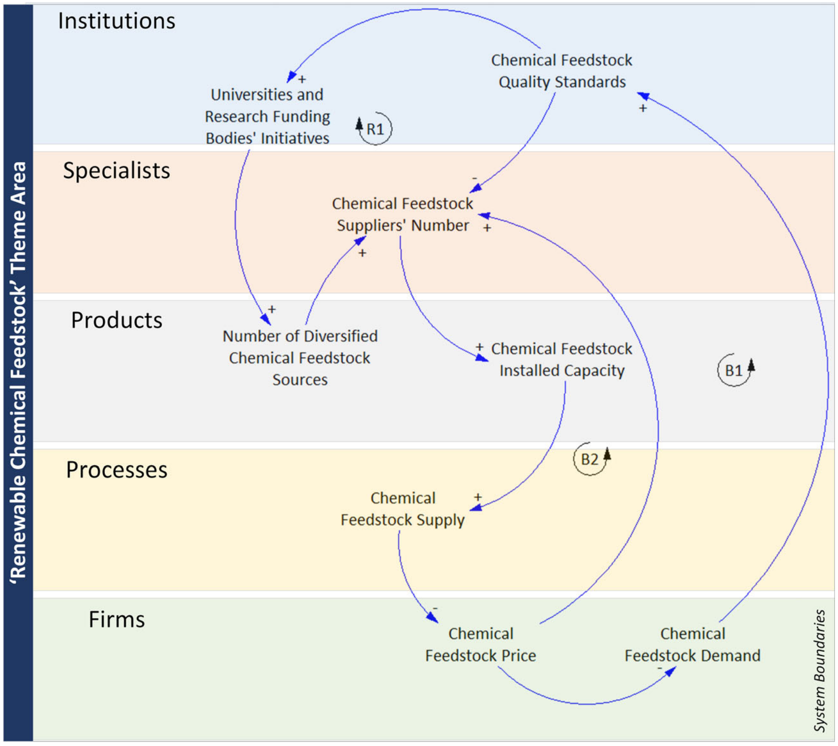


Fig. 3 Industrial system mapping for 'green' pharmaceuticals – 'Renewable Chemical Feedstock' theme area

of funding initiatives. Furthermore, institutional bodies responsible for ensuring and promoting public health have to approve and certify those innovations to allow for their adoption by the actors at each supply chain echelon. Then, manufacturers will be able to plan their capacity and schedule the production volumes of the selected API, the range of dosage forms and the number of packages necessary to cover the projected market demand.

Similarly to the 'Renewable Chemical Feedstock' theme area, the complexity and non-linear behaviour in the 'Technology' theme area is captured through corresponding feedback loops. Indicatively, in the reinforcing loop R2, an increase in the '*Packaging Manufacturing Rate*' implies increased '*Pharmaceuticals' Number of Packages*', which in turn results in elevated '*Packages' Inventory*'. The conceptual system under study is illustrated in Fig. 4 via the relevant causal loop diagram.

5.3 Market

Demand for medications is commonly expressed in terms of packages of dosage forms and can be considered stochastic in nature, often estimated by historical data over actual dispensed quantities. Particularly, the demand function should be formulated based on statistics gathered by national healthcare systems to forecast the anticipated quantities to be prescribed by either pharmacy contractors, dispensing doctors and appliance contractors, or dosage units supplied under personal administration. Notably, marketing professionals and academics alike should consider that branded and generic pharmaceuticals follow different life cycle patterns. Therefore, they have to explore different avenues for finding appropriate forecasting models for pharmaceutical data to then allow companies in the sector to prepare relevant marketing strategies and implement recommended inventory control policies (Nikolopoulos et al. 2016). Following the circular economy notion, for the case of generic pharmaceuticals like paracetamol, consumers could be environmental sensitive towards the sustainable nature of the offered medications (Tsolakis and Srai 2017), hence highlighting future market opportunities.

National healthcare systems comprise the major direct market for pharmaceutical firms while these further approve the dosage forms to be prescribed by medical specialists and dispensed by generic retailers to a specific market. Thereafter, wholesalers, retailers and logistics services' providers should apply appropriate inventory control and management policies to avoid product stock-outs and price inflations.

Analogously to the previously examined theme areas, the complex nature and the non-linear system functionality in the 'Market' theme area is appreciated through the respective feedback loops. For example, in the balancing loop B4, lessen '*National Healthcare System Regulations*' that allow greater financial support to the national healthcare sector would result in enhanced '*Doctors' and*

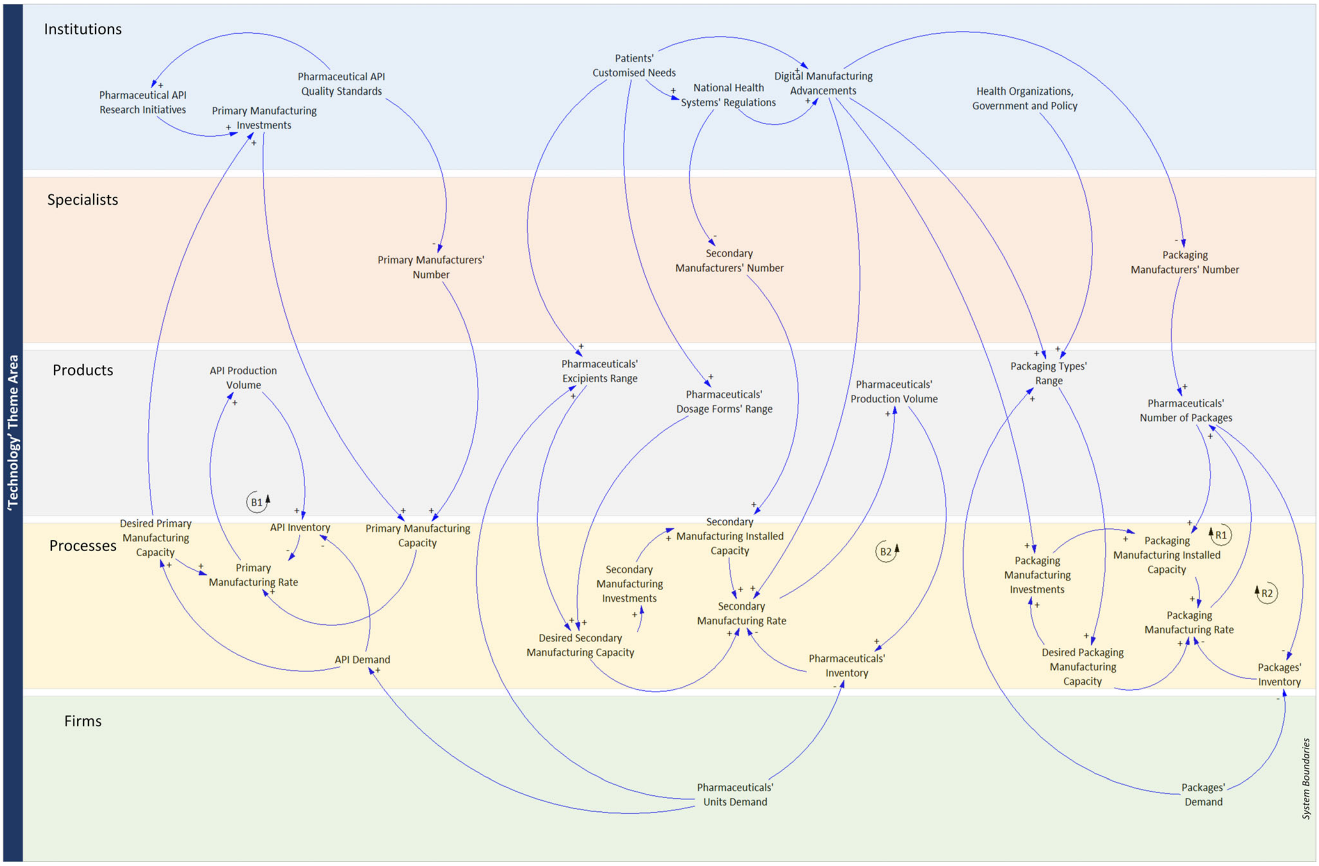


Fig. 4 Industrial system mapping for 'green' pharmaceuticals – 'Technology' theme area

Practitioners' Prescriptions'. The increased number of prescriptions augments the '*Demand for Packaging Units of Pharmaceutical Dosage Forms*', which in turn lowers the '*Retailers' Pharmaceuticals' Inventory*'. A lower inventory typically increases, either in number or size, the '*Orders for Packaged Pharmaceuticals*', thus further motivating '*Research & Development Initiatives for Pharmaceutical Alternatives*'. Research and development in 'green' pharmaceuticals are necessitated as renewable chemical feedstocks can expand the installed capacity for the synthesis of either existing or novel pharmaceuticals' API. Figure 5 visualises the causal loop diagram that captures the connections and interrelations among the system's variables.

5.4 Value and viability

Following a supply chain perspective, devising robust and commercially viable renewable feedstock-based networks requires consideration of key issues (Gold and Seuring 2011), like: limited availability of key compounds, constrained production capacity of existing platform technologies, dispersed geographical allocation of network echelons, and applied risk mitigation strategies to secure continuity of business operations. More specifically, in the pharmaceutical sector, value is primarily harnessed through delivering medication safety and efficacy while economic viability is ensured through the respective monetary flows from downstream to upstream supply chain operations. Following that, personalisation of pharmaceuticals based on individual patients' healthcare profile should be positioned at the core of every medical treatment solution (Stegemann 2015).

To foster supply chain value and commercial viability, a pharmaceutical product has to be acclaimed by both medical and consumers' associations, while for 'green' medications environmental groups can have a significant role in supporting the provision of environmentally sustainable offerings. Following that, doctors and practitioners could be inclined towards prescribing 'green' pharmaceuticals that both have: (i) similar or even improved pharmacological properties to conventional medications, and (ii) reduced environmental impact from an end-to-end supply network perspective. The elaboration of third-party logistics services providers to outsource any closed-loop network operations could support the efforts towards better management of pharmaceutical waste streams and possibly circulation of production resources.

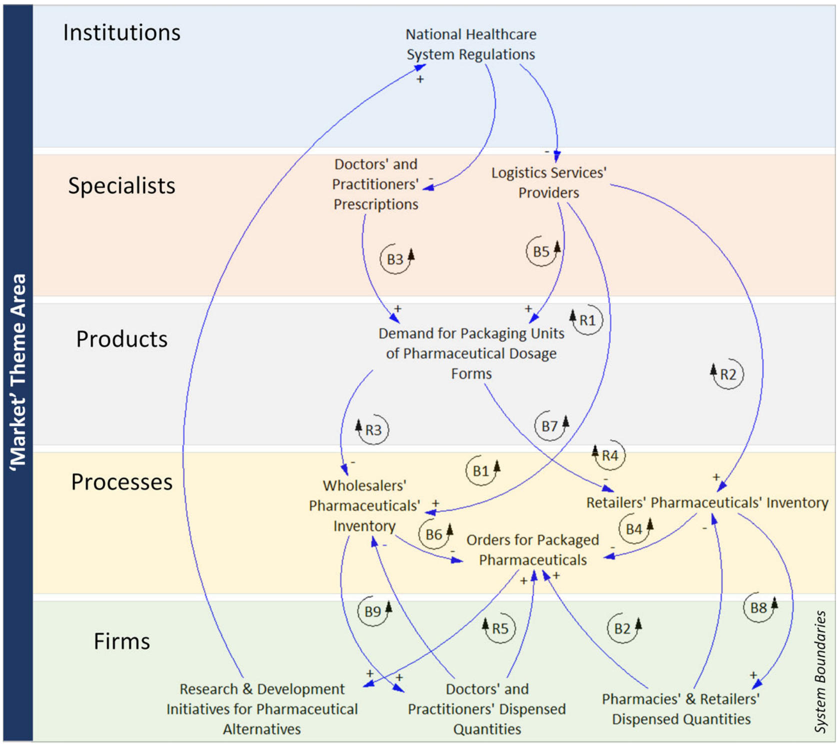


Fig. 5 Industrial system mapping for 'green' pharmaceuticals – 'Market' theme area

Alike the previous three theme areas, the complex interrelations and the dynamic functionality of the 'Value and Viability' theme area is captured through the relevant feedback loops. Indicatively, in the balancing loop B1, increased '*Doctors' and Practitioners' Prescriptions*' result in augmented demand and consumption of '*Pharmaceutical Dosage Units*', which in turn increases the discarded '*Pharmaceutical Waste Volumes*'. In closed-loop supply networks of specific nature, like in the pharmaceutical industry, an increased amount of waste necessitates the establishment of more contractual agreements with '*Third-Party Logistics Services Providers*' to address the enhanced '*Pharmaceutical Waste Recovery Volumes*'. However, the increased closed-loop operations of 'green' pharmaceuticals that contain chemical feedstocks, which could be recovered for the synthesis of similar APIs, mediate the '*Environmental Groups' Complaints*' thus motivating '*Doctors' and Practitioners' Prescriptions*' on renewable feedstock-based pharmaceuticals. Figure 6 illustrates the corresponding interrelations among the involved actors and system's entities.

6 Integrated mapping methodology and network transformation drivers

Herein, we propose a contextual mapping approach for the ex-ante capturing of the dynamics underpinning industrial systems arising from renewable feedstocks, with a particular focus on the pharmaceutical sector. Our methodology differs from existing mapping approaches which suggest a static view on circular supply systems. Specifically, this study provides a strategic approach for capturing the dynamically evolving transformation phenomena in end-to-end supply chains across the feedstock, technology, market, and value and viability theme areas. Below, the integrated mapping approach is presented. Following that, we briefly discuss the major external drivers that give impetus for transformations and (re)configurations in renewable feedstock-based supply networks.

6.1 Dynamic mapping approach

The presented mapping approach systematically captures the dynamics among institutional stakeholders, industrial actors, material/product transformations and processing technologies, and firms, following a supply chain perspective. The analysis also extends to four interconnected and mutually interacting theme areas, namely "renewable chemical feedstock – technology – market – value and viability", which are fundamental for exploring supply chain (re)configuration opportunities arising from renewable feedstocks. The applied approach enables the effective cross-theme area analysis towards

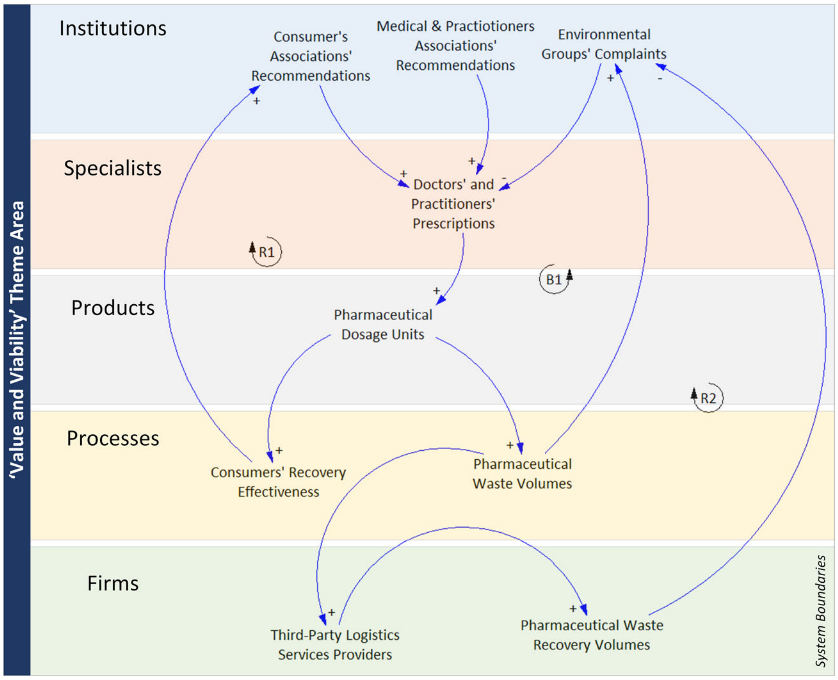


Fig. 6 Industrial system mapping for 'green' pharmaceuticals – 'Value and Viability' theme area

comprehending the critical industrial systems' mechanisms along with the recommended data gathering tools and sources. The System Dynamics view of the proposed mapping approach enables the understanding of the connections, level of engagement and causalities among the different actors across industrial value chains. We argue from theory and a synthesis of empirical findings that decision-makers should explore alternative supply chain (re)configuration options considering that the four theme areas of analysis are interconnected and mutually interacting, as depicted in Fig. 7. Direct linkages among stakeholders and product/process entities, among different themes areas, are case dependent and should be considered. The effectiveness of the proposed mapping approach is discussed for the case of pharmaceutical industrial systems focusing on the exemplar case of 'green' paracetamol. More specifically, we indicate generic emergence patterns from a supply chain perspective that stakeholders and actors should reflect to ensure business competitiveness within the today's circular economy era.

The review of selected industrial systems' mapping techniques along with the provided approach indicate that mapping approaches should reflect the granularity levels of the intended outputs (Srai 2017). For pharmaceutical industrial systems, a cross-case analysis could foster the identification of sector specific emerging trends and challenges to better inform local industry and policy-makers to outline realistic interventions and value chain reforms. In addition, operations research scholars are recommended to maintain and compare systems' maps over several time horizons to further enable the analysis of industry-specific patterns of progressive evolution that are particularly evident in the pharmaceutical sector.

The mapping methodology developed in this research provides a basis for conceptualising industry transformations and facilitates industry evolution through capturing the dynamic relations among enablers in industrial manufacturing sectors. Our proposed framework differs from the original business model canvas approach proposed by Osterwalder and Pigneur (2010), principally in terms of the considered feedback effects and the inclusion of causal loops and inherent polarity. In addition, the business model canvas does not take into consideration any potential innovations (Joyce and Paquin 2016); our proposed approach specifically elaborates on the 'Technology' theme area. Another key differentiating element of our approach is the consideration of major external factors to a supply system (e.g. policies), a building block that is neglected by Osterwalder and Pigneur (2010).

6.2 Supply chain (re)configuration drivers

Through the analysis of the cross-dynamics captured via the provided mapping process, we can identify three main external drivers that foster transformations and supply chain (re)configuration opportunities and impact the respective systems' long-term commercial viability. The

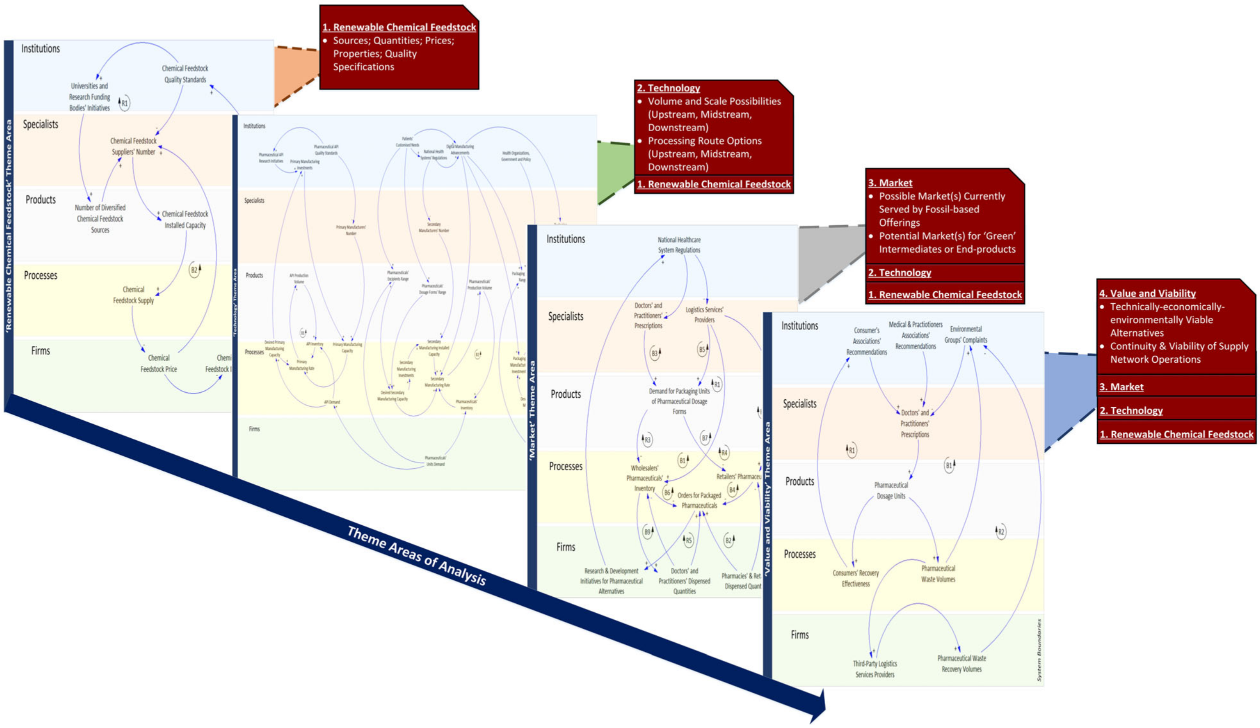


Fig. 7 Multi-stage multi-layer mapping methodology for industrial network systems enabled by renewable chemical feedstocks

identified drivers span catholically across the four theme areas of analysis and should be evaluated on a multi-stage multi-layer perspective to better inform decision-makers and analysts about sustainable and commercially viable options.

Firstly, regulations have a detrimental role in supporting the diffusion of renewable feedstocks to industrial applications in geographically diversified markets. For example, the demand and production of biofuels from biomass and agricultural residues was increased in the United States of America mainly due to the legislation enacted by the Energy Independence and Security Act of 2007 (Castillo-Villar et al. 2017). In the pharmaceutical industry, governmental regulations should contemporarily ensure the triplet “quality – safety – efficacy” of renewable feedstock-based medications (Desai et al. 2018) and alleviate sectoral barriers to growth (Festel 2011). In particular, owing to the often volatile physicochemical properties of renewable feedstocks, regulatory requirements concern about potential changes in the properties of excipients and biopharmaceuticals’ API during the scale-up and down-stream production processes that could hinder manufacturing consistency and reproducibility (Parr et al. 2016). During the last decades, Desai et al. (2018) report that pharmaceutical industry experts and regulators from the United States, Europe, and Japan have jointly worked towards streamlining, harmonising, and accelerating the development and approval processes of new bio-based pharmaceutical products. Institutional arrangements and regulations could benchmark market needs and drive the use of renewable feedstocks for specific offerings; then technology advancements could be supported to promote value creation in a synergistic manner. Indicatively, for the case of ‘green’ paracetamol, renewable chemical feedstocks like terpenes posse a promising alternative to petrochemicals that can be found either as a by-product during the pulp digestion in kraft paper mills (Roberge et al. 2001; Yumrutaş et al. 2008) or in citrus waste generated in significant volumes by the citrus (i.e. orange and orange juice) industry (Negro et al. 2016).

Secondly, bio-based fine chemicals’ manufacturing requires that synthesis routes for the value-added offerings are developed, tested and optimised at a laboratory and unit operations scale (Jiménez-González et al. 2011), respectively. Thereafter, the future of bio-based supply networks relies on either the technical capability to integrate novel synthesis routes to existing infrastructure and processing facilities (Lapkin et al. 2017), or the economic feasibility of investments in new biorefineries (Gunukula et al. 2018). Especially, commercialisation of new biopharmaceutical molecules requires consideration of key technoeconomic parameters (Mupondwa et al. 2015), including: medications' biological and pharmacological potency, capital investment and operating costs, market uncertainty analysis, production scalability and profitability. In terms of primary manufacturing, the selection of the renewable feedstock for manufacturing the API has major repercussions in terms of the utilised equipment and chemical synthesis routes, always complying with the intermediate and/or end-product specifications required by the market. Despite existing knowledge about pharmaceuticals' chemical synthesis pathways, detailed data for manufacturing 'green' medications at an industrial scale are sparse. For example, Settanni et al. (2016) report that classic routes to synthesise paracetamol are principally based on a reduction-acetylation system (Mitchell and Waring 2002). On the other hand, a promising 'green' chemistry route for the synthesis of paracetamol is documented to be based on the amination of hydroquinone (Joncour et al. 2014).

Thirdly, uncertainty conditions, particularly on the market demand side of 'green' offerings in a circular economy landscape, create domino effects to the manufacturing processes thus shaping dynamic negotiations and interactions among supply chain actors (Primo 2010). A demonstrable-confirmed efficacy of biopharmaceuticals and their acceptance by the healthcare community will contribute to the growing market demand for such 'green' medications (Kesik-Brodacka 2018). Demand for 'green' pharmaceuticals could be projected through available historical data from prescriptions for both patented and generic corresponding medications (Makridakis and Hibon 2000). Conversely, conceptualising the impact of the pharmaceuticals' 'green' image on the respective demand patterns could unveil further market opportunities; however, capturing the 'green' image dynamic effects is rather ambiguous to understand and requires the elaboration of specific modelling methods. For the case of 'green' paracetamol, the market diffusion dynamics are closely related to inventory management requiring counterfactual analysis (Tsolakis and Srai 2017).

To sum up, three external drivers are fuelling dynamic transformations in supply networks enabled by renewable feedstocks, namely: (i) regulatory conformance with market requirements, (ii) system level technoeconomic feasibility assessment of specified renewable feedstocks, and (iii) target market volume demand. To this effect, the competitiveness and commercial viability of the respective industrial network systems could be ensured by mapping and comprehending the sources of these drivers.

7 Discussion and conclusions

Hitherto the prevalent trend in the industrial domain implies that manufacturers locate their production facilities in emerging economies (Lai and Wong 2012; Tang and Zhou 2012) to benefit from the inexpensive labour, low-cost petrochemical-based materials and unsustainable manufacturing processes due to the absence of strict environmental policy constraints (Lai et al. 2013; Hirschnitz-Garbers et al. 2016). Nevertheless, a range of issues affecting industries located in both Western and developing countries, including rising labour expenditures, strict environmental regulations, consumers' sustainability awareness, elevated shipping costs, radical innovations in manufacturing technologies and chemical synthesis pathways, and rising productivity and reliability concerns, are triggering shifts in the scale and distribution of production systems (Ford and Despeisse 2016; Stentoft et al. 2016). Especially, sustainability concerns and advances in manufacturing technologies and production processes encourage both global industries and local organisations to (re)configure their production and supply bases to enable more cost and resource efficient manufacturing that is both sustainable and responsive to personalised market demand (Ray and Ray 2012; Ancarani et al. 2015).

In this regard, this research addresses the challenge of mapping industrial network systems arising from renewable feedstocks. The study is grounded on three research questions and applies alternative methodologies in an attempt to tackle them. More specifically, RQ#1 concerns the sufficiency of existing mapping methodologies and it is answered through a critical taxonomy of the extant literature. Literature findings regarding the mapping of evolving industrial network systems illustrate that mapping techniques combining System Dynamics elements could be very efficient strategic management tools. In an attempt to answer the second research question of this study (RQ#2), we synthesise theoretical constructs identified in the literature and we propose a stepwise mapping framework and an integrated mapping approach that combines structural elements from the Industrial Systems Mapping and System Dynamics theory. Additionally, experts' opinion informs the application of the proposed mapping approach to the case of ‘green’ pharmaceuticals, by particularly examining the illustrative case of paracetamol. Finally, RQ#3 is addressed via a synthesis of secondary literature findings, along with business and research expertise.

The purpose of this research is to provide a mapping methodology for capturing the macro-level interactions among the essential structural elements of future industrial supply chains, specifically dealing with renewable chemical compounds, that could then inform stakeholders about network (re)configuration dynamics. The approach can guide managers’ decision-making process towards the effective analysis and planning of alternative material sourcing, production and supply chain operation strategies. Particularly, the proposed approach builds upon the principles of the System Dynamics theory to capture the dynamic nature of complex industrial systems. The causal loop elements and the feedback mechanism of the provided mapping technique indicate that the approach could act as an enabler to support the analysis of transformation dynamics in circular industrial systems arising from renewable feedstocks. The standardisation elements of the provided visualisation technique indicate that the proposed mapping approach could support specific case and cross-industry comparative analyses. Furthermore, the provided approach enables the investigation of scenarios that capture a wide range of interdependent behaviours for renewable feedstock-based supply systems as regards to assumptions/projections about forthcoming policies, possible market structures and alternative technology options (Jeffers et al. 2013). The case of ‘green’ paracetamol is selected as a promising exemplar study to demonstrate the applicability of the proposed mapping approach, embracing alternative raw material sources, technologies, markets and value capture opportunities.

This study contributes to sustainable supply chain research by providing a multi-stage multi-layer mapping methodology for capturing the dynamics that govern ‘green’ pharmaceutical supply systems enabled by renewable chemical feedstocks in order to foster their competitiveness and economic viability. This mapping process needs to be replicated from the macroscopic to the mesoscopic and microscopic scales to capture the realistic pharmaceutical industrial systems’ interactions among the identified stakeholders and product/process entities, across the four theme areas of analysis. For this to be effective, after the completion of the macroscopic analysis, the mapping process should follow the reverse order and be re-performed from the micro to the meso and to the macro-level, respectively. This iterative process allows for the validation and verification of future industrial systems. Through the analysis of the cross-dynamics captured via the provided mapping methodology we can identify three main drivers that could foster transformations and supply chain (re)configuration opportunities, namely: (i) regulatory conformance with market requirements, (ii) system level technoeconomic feasibility assessment of specified renewable feedstocks, and (iii) target market volume demand. To this effect, the competitiveness and commercial viability of the respective industrial systems could be ensured. Overall, this research assists in introducing renewable feedstocks to institutional and business operational agendas, further unveiling future research avenues in the operations management field.

In terms of limitations, the current study provides a high-level approach and needs to be tested and refined for particular case studies of pharmaceutical offerings and for specific markets. The provided mapping approach has a macroscopic view of the supply chain configuration with logistics and geographical distribution of different supply network operations not being sufficiently embraced at a tactical and/or operational level. To that end, mesoscopic and microscopic level dynamics analyses need to be applied once the perspective and boundaries of research are determined. Furthermore, the provided approach does not capture the magnitude of material or monetary flows.

Considering potential future research within the pharmaceutical sector, we are focusing on mapping and understanding the clinical trial value chains in order to develop a comprehensive mapping approach that integrates both medication and patient-centric perspectives (Harrington et al. 2016). Furthermore, the present research would benefit from being further extended to embrace complexity and uncertainty issues for fostering the adaptability and resilience of evolving industries enabled by renewable feedstock platform technologies. Except for supporting the transition towards a circular economy, the developed mapping approach could be also utilised in consumer-centric or technology-disruptive manufacturing systems, rather than renewable raw material-centric supply networks. In the latter case, the macro-level industrial map would focus on the ‘technology – market – raw material – value and viability’ analysis sequence. In the pharmaceutical context, where technology interventions support patient-centric healthcare services, this revised sequence can be applied by researchers and stakeholders alike to investigate evolving (re)configuration dynamics stemming from the utilisation of digital supply chain technologies (Goyanes et al. 2015; Holmström et al. 2016).

Acknowledgements This research has received funding from the EPSRC under Grant Reference No. EP/K014889/1, Project Title: “Terpene-based Manufacturing for Sustainable Chemical Feedstocks”, and the Advanced Manufacturing Supply Chain Initiative under the AMSCI Grant No. TS/L006529/1, Project Title: “ReMediES – Reconfiguring Medicines End-to-End Supply”.

Appendix 1

Table 2 Structure of Feedback Loops

Theme Area	Feedback Loop	Causal Effect Sequence
Renewable Chemical Feedstock	R1	Chemical Feedstock Quality Standards → Universities and Research Funding Bodies' Initiatives → Number of Diversified Chemical Feedstock Sources → Chemical Feedstock Suppliers' Number → Chemical Feedstock Installed Capacity → Chemical Feedstock Supply → Chemical Feedstock Price → Chemical Feedstock Demand → Chemical Feedstock Quality Standards
	B1	Chemical Feedstock Quality Standards → Chemical Feedstock Suppliers' Number → Chemical Feedstock Installed Capacity → Chemical Feedstock Supply → Chemical Feedstock Price → Chemical Feedstock Demand → Chemical Feedstock Quality Standards
	B2	Chemical Feedstock Suppliers' Number → Chemical Feedstock Installed Capacity → Chemical Feedstock Supply → Chemical Feedstock Price → Chemical Feedstock Suppliers' Number
Technology	R1	Packaging Manufacturing Installed Capacity → Packaging Manufacturing Rate → Pharmaceuticals' Number of Packages → Packaging Manufacturing Installed Capacity
	R2	Packaging Manufacturing Rate → Pharmaceuticals' Number of Packages → Packages' Inventory → Packaging Manufacturing Rate
	B1	Primary Manufacturing Rate → API Production Volume → API Inventory → Primary Manufacturing Rate
	B2	Secondary Manufacturing Rate → Pharmaceuticals' Production Volume → Pharmaceuticals' Inventory → Secondary Manufacturing Rate
Market	R1	National Healthcare System Regulations → Logistics Services' Providers → Wholesalers' Pharmaceuticals' Inventory → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	R2	National Healthcare System Regulations → Logistics Services' Providers → Retailers' Pharmaceuticals' Inventory → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	R3	National Healthcare System Regulations → Doctors' and Practitioners' Prescriptions → Demand for Packaging Units of Pharmaceutical Dosage Forms → Wholesalers' Pharmaceuticals' Inventory → Doctors' and Practitioners' Dispensed Quantities → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	R4	National Healthcare System Regulations → Doctors' and Practitioners' Prescriptions → Demand for Packaging Units of Pharmaceutical Dosage Forms → Retailers' Pharmaceuticals' Inventory → Pharmacies' & Retailers' Dispensed Quantities → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	R5	National Healthcare System Regulations → Logistics Services' Providers → Demand for Packaging Units of Pharmaceutical Dosage Forms → Wholesalers' Pharmaceuticals' Inventory → Doctors' and Practitioners' Dispensed Quantities → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	B1	National Healthcare System Regulations → Logistics Services' Providers → Wholesalers' Pharmaceuticals' Inventory → Doctors' and Practitioners' Dispensed Quantities → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	B2	National Healthcare System Regulations → Logistics Services' Providers → Retailers' Pharmaceuticals' Inventory → Pharmacies' & Retailers' Dispensed Quantities → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	B3	National Healthcare System Regulations → Logistics Services' Providers → Demand for Packaging Units of Pharmaceutical Dosage Forms → Wholesalers' Pharmaceuticals' Inventory → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	B4	National Healthcare System Regulations → Doctors' and Practitioners' Prescriptions → Demand for Packaging Units of Pharmaceutical Dosage Forms → Retailers' Pharmaceuticals' Inventory → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	B5	National Healthcare System Regulations → Logistics Services' Providers → Demand for Packaging Units of Pharmaceutical Dosage Forms → Retailers' Pharmaceuticals' Inventory → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	B6	National Healthcare System Regulations → Doctors' and Practitioners' Prescriptions → Demand for Packaging Units of Pharmaceutical Dosage Forms → Wholesalers' Pharmaceuticals' Inventory → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations

Table 2 (continued)

Theme Area	Feedback Loop	Causal Effect Sequence
	B7	National Healthcare System Regulations → Logistics Services' Providers → Demand for Packaging Units of Pharmaceutical Dosage Forms → Retailers' Pharmaceuticals' Inventory → Pharmacies' & Retailers' Dispensed Quantities → Orders for Packaged Pharmaceuticals → Research & Development Initiatives for Pharmaceutical Alternatives → National Healthcare System Regulations
	B8	Retailers' Pharmaceuticals' Inventory → Pharmacies' & Retailers' Dispensed Quantities → Retailers' Pharmaceuticals' Inventory
	B9	Wholesalers' Pharmaceuticals' Inventory → Doctors' and Practitioners' Dispensed Quantities → Wholesalers' Pharmaceuticals' Inventory
Value and Viability	R1	Doctors' and Practitioners' Prescriptions → Pharmaceutical Dosage Units → Consumers' Recovery Effectiveness → Consumer's Associations' Recommendations → Doctors' and Practitioners' Prescriptions
	R2	Doctors' and Practitioners' Prescriptions → Pharmaceutical Dosage Units → Pharmaceutical Waste Volumes → Third-Party Logistics Services Providers → Pharmaceutical Waste Recovery Volumes → Environmental Groups' Complaints → Doctors' and Practitioners' Prescriptions
	B1	Doctors' and Practitioners' Prescriptions → Pharmaceutical Dosage Units → Pharmaceutical Waste Volumes → Environmental Groups' Complaints → Doctors' and Practitioners' Prescriptions

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