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Research article

The spatial dynamics of deep transitions

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ABSTRACT

Industrial societies are currently evolving along a fundamentally unsustainable trajectory, contributing to climate change, resource depletion and loss of biodiversity. A recent Deep Transitions framework (Schot and Kanger, 2018; Kanger and Schot, 2019) argues that this trajectory has been built up through the First Deep Transition: a 250-year co-evolution of multiple socio-technical systems. However, to date the Deep Transitions framework has completely neglected the spatial dimension of this process. This makes it unable to explain (1) how socio-technical systems emerge in, gravitate towards, become linked in and disperse from certain locations; (2) how global constraints condition actors' responses in specific locations and how these responses, in turn, reproduce or transform socio-technical systems; (3) how these processes accumulate into socio-material landscapes, posing locationally varying constraints to major transformative change. As a response this paper aims to develop a middle-range theory of the spatial dynamics of Deep Transitions. Synthesizing insights from a broad range of fields nine propositions are developed on the spatial patterns and mechanisms of long-term multi-system co-evolution. The resulting framework enables to explain the spatial genesis of the First Deep Transition and opens up a research agenda for studying the possibly emerging Second Deep Transition.

1. Introduction

The world is confronted by a socio-ecological crisis, manifesting itself through climate change, resource depletion and loss of biodiversity (Haberl et al., 2019; IPBES, 2019; IPCC, 2021). It is increasingly understood that these problems have been generated by a broad range of socio-technical systems underpinning industrial societies and fulfilling various societal functions such as energy, mobility, food, water or housing. In the rapidly growing socio-technical transitions field (Geels, 2002; Grin et al., 2010; Köhler et al., 2019) much work has thus been done to identify the broad patterns and driving mechanisms of systems change as well as the possibilities for accelerating transitions towards sustainable and just directions.

Despite some pioneering exceptions (e.g. Geels, 2007; Raven and Verbong, 2009; Papachristos et al., 2013; Sutherland et al., 2015) existing work on transitions has primarily focused on single systems. Lately, however, the need for 'zooming out' has been increasingly advocated (Köhler et al., 2019: 6) in order to shift "emphasis away from within system dynamics that have received considerable attention to the interconnected and multi-scalar qualities of socio-technical systems that are less well understood" (Rosenbloom, 2020: 339).

A recently developed Deep Transitions (DT) framework (Schot and Kanger, 2018; Kanger and Schot, 2019) is an attempt to answer

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this call. Synthesizing insights from sustainability transitions studies (Grin et al., 2010), neo-schumpeterian version of long wave theory (Freeman and Louçã, 2001) and industrialization literature (Stearns, 2013) DT theorizes how interactions between socio-technical systems generate 40-60 year 'great surges of development' (Perez, 2002) and how successive surges, in turn, accumulate into a set of principles driving every industrial society – an industrial modernity. The authors of the DT framework argue that the 250-year co-evolution of single systems, interconnected systems and industrial modernity – the First Deep Transition – has created a fundamentally unsustainable trajectory of environmental degradation while not being able to solve recurring problems of social inequality. Altering the situation requires a shift of comparable magnitude – the Second Deep Transition.

In terms of its scope – linking major historical discontinuities and continuities over a very long time frame on multiple levels – DT is the first to offer a comprehensive theory of industrial modernization as an outcome of multi-system co-evolution. However, the framework has also been criticized for its emphasis on broad structural patterns to the relative neglect of actors shaping transitions (van der Vleuten, 2019). Furthermore, existing work has so far focused on the unfolding of Deep Transitions over time while neglecting the spatial dimension of this process. As a result the DT theory in its current state cannot explain the emergence and perpetuation of locational variation in co-evolving socio-technical systems over long time-frames, or the role of actors in this process. In other words, the framework does not offer an account of the spatial genesis of the First Deep Transition nor does it enable to identify places most likely to enact transformative change on the scale of the Second Deep Transition. Existing studies on the spatial aspects of socio-technical change might help to address these shortcomings. Yet at present potentially useful insights remain scattered between disciplines – including but not limited to innovation studies, evolutionary economic geography, transitions studies, history of technology and macro-sociology – without adding up to a coherent whole. A theoretical synthesis on the scale that gave rise to the initial DT framework is required to overcome this impasse.

This paper takes up the challenge aiming to sketch the contours of a spatial theory of Deep Transitions. Owing to the scope of the task, it does so in a particular manner, however. The primary aim of the paper is to develop a middle-range theory: a limited set of interrelated propositions aimed at understanding a particular phenomenon, that is, the spatial dynamics of Deep Transitions. As such the article largely abstains from engaging in grand metatheoretical debates on space and scale (see MacKinnon, 2010, for a concise summary of these issues in human geography; see also Miörner and Binz, 2021, for the contextualization of this debate in transitions studies). There are two reasons behind this choice. First, as middle-range theories are phenomenon-oriented, they often combine conceptual insights from various schools of thought. As a result such theories frequently avoid adopting extreme metatheoretical positions (e.g. idealist versions of social constructivism or flat ontology), or simply remain underdetermined in relation to metatheoretical postulates (e.g. by having a set of propositions that are able to accommodate the existence of both objective and subjective constraints to agency). In other words, for middle-range approaches metatheories often function as sensitizing devices, guiding attention to particular facets of reality. This is well exemplified by Geels (2010) who shows that the Multi-level Perspective, a middle-range theory originally developed to explain how and why radical system shifts occur (Geels, 2002), can have crossovers with very different ontologies (even when some of them may have less relevance for transitions research). An additional, more pragmatic consideration is that extensive engagement in metatheoretical debates would threaten to direct attention away from the main goal of the paper, i.e. formulation of a middle-range theory of the spatial patterns and mechanisms of multi-system co-evolution. Hence the following will focus on the middle-range propositions, keeping metatheoretical discussions to the necessary minimum.

The ambition of the task also shapes the paper's style of theorizing. Similarly to the initial formulations of the DT framework (Schot and Kanger, 2018; Kanger and Schot, 2019), the article exercises 'appreciative theorizing' (Nelson and Winter, 1982: 46) in the spirit of 'analytic eclecticism' (Sil and Katzenstein, 2010). That is, instead of conducting an exhaustive literature review of a broad range of fields (only to end up discarding most of it), the paper will draw directly on recurring findings on the spatial dynamics of socio-technical change from different disciplines deemed relevant for conceptualizing the geography of multi-system co-evolution. This entails challenging the reader to undertake a journey to a hitherto unexplored theoretical terrain and, in so doing, inviting one to engage in a critical yet constructive dialogue with the propositions on offer.

The paper is structured as follows. Section 2 outlines the main features of the DT framework and discusses its two oversights: relative neglect of actors and lack of attention to the spatial dimension. Building on this discussion, Section 3 summarizes findings from different disciplines on the spatial dynamics of socio-technical change as seven stylized facts. These effectively provide a commonly shared factual base that the spatial theory of Deep Transitions would need to integrate. Connecting these stylized facts to the conceptual vocabulary of the DT framework, Section 4 will then outline nine propositions on the spatial patterns and mechanisms of Deep Transitions paying particular attention to three aspects: (1) emergence, gravitation, linking and dispersion of socio-technical systems; (2) global structural constraints and local actor responses; (3) the generation of locationally varying socio-material landscapes. Each proposition is illustrated with historical examples to make the general claims more tangible. Section 5 concludes with a research agenda, showing how the theory offered in the paper opens up new ways for studying the possibly emerging Second Deep Transition.

2. The Deep Transitions framework

The DT framework was initially developed to address two gaps in existing knowledge on multi-system co-evolution: to theorize how transitions in single systems relate to 'long waves' or 'great surges of development' (Schot and Kanger, 2018), and to understand how successive surges accumulate into major historical continuities characterizing the overall industrialization process (Kanger and Schot, 2019). In order to conceptualize these links the framework places an emphasis on rules – "humanly devised constraints that structure human action, leading to regular patterns of practice" (Schot and Kanger, 2018: 1053) – as a central coordination mechanism. By being embedded in the very structure of socio-technical systems rules shape the behaviour of actors and provide systems with long-lasting directionality. This approach places DT at the crossroads of evolution theory, sociological structuration theory and institutional theory

(ibid.).

Schot and Kanger (2018) developed a rule-based model connecting processes on niche- and regime-level as described by the Multi-level Perspective on socio-technical transitions (Geels, 2005; Grin et al., 2010), to successive 'great surges of development' as conceptualized by Carlota Perez. Perez (2002) argues that since the late 18th century there have been five 40−60 year surges[1], each characterized by particular periods: (1) gestation (pre-surge period); (2) installation period (first half of the surge, lasting about 20−30 years); (3) turning point; (4) deployment period (second half of the surge, also lasting 20−30 years). According to the model the emergence, alignment and consolidation of rules is related to these periods as follows:

1 A protracted gestation period is characterized by the emergence, circulation and partial alignment of new rules rules in separate niches, i.e. spaces governed by specific selection criteria such as military applications prioritizing performance over cost. In exceptional instances these rules may become aligned into a rule-set (called 'regime') with distinctively novel qualities. For example, van den Ende and Kemp (1999) identify manual/mathematical instrument, scale model, analogue computing, small office technology and punch card regimes in the fields of scientific/technical computing and data processing between 1900s and 1960s as precursors of the digital computing regime.
2 In the early installation period emerging and incumbent rules come to compete with each other, resulting in transitions (or transition failures) in single systems. Some rules may also start to cross the boundaries of several systems, thereby turning into 'meta-rules'. Through the establishment of various couplings between systems and the work of transnational actors these meta-rules gradually start to align to each other, thereby turning into 'meta-regimes', i.e. rule-sets coordinating multiple systems. As a result, a clearer new directionality becomes visible. For example, from the 1970s various principles related to computing, data processing, software design, networking and communications increasingly connected the formerly separate regimes of digital computing, data communication, telecommunication and mass communication (van Dijk, 2005: 7).
3 The competition between meta-rules and their various combinations is resolved at the turning point. Major crises provide an impetus for the alignment of expectations, enabling powerful actors to tilt the playing field in favour of a particular rule-set. Therefore, from this point forward one can start talking about the existence of *the* dominant meta-regime providing directionality across many socio-technical systems. Examples are the dot-com bubble and 9/11 in 2001 which made it easier for Google to introduce what Zuboff (2019) calls 'surveillance capitalism'. Connecting ICT to market imperatives surveillance capitalism includes a set of interrelated principles such as treating human experience as a free raw material, using this 'behavioural surplus' for the fabrication of prediction products, and trading these predictions in behavioural futures markets (ibid: 8).
4 During the early deployment period the now-dominant meta-regime selects niches compatible with its logic, continues to diffuse to new systems, and starts to shape the broader socio-material 'landscape'. For example, at present the impact of the 'digitalization' meta-regime can be observed across systems such as energy (smart grids), transport (mobility-as-a-service, self-driving vehicles) or food (DIYbio) (Tylecote, 2019). Digitalization has also contributed to social inequality and environmental degradation, e.g. through the emergence of a 'digital divide' (van Dijk, 2020: 134-145), or the impacts of cryptocurrency mining on fossil fuel based energy consumption (Krause and Tolaymat, 2018). Over time the accumulation of broader socio-environmental impacts gradually starts to provoke increasing contestation of the meta-regime from various actors. The scene is set for yet another surge with rules in new niches and systems becoming the main loci of radical innovation.

Building on this work, Kanger and Schot (2019) propose that whereas each surge indeed pioneers a new meta-regime, some rules from each surge prove to be so useful that they are retained by a broad range of actors. This repository of rules, accumulating from one surge to another, is called industrial modernity. Being shared by every industrial society, these rules generate various long-term trends and persistent problems (see ibid.: 12, for a full list). Examples include assumptions that waste is not a problem and that resources are endlessly substitutable through continued technological innovation. Actions based on these assumptions contribute to increasing energy and materials usage per capita (Haberl et al., 2019) and to pervasive rebound effects where increasing technological efficiency is offset by corresponding rise in demand (Magee and Devezas, 2017). An example of a more recent addition to the repertoire of industrial modernity is the use of science as an input to engineering. This principle was pioneered during the 3rd surge by Friedrich Bayer Company, establishing the first industrial research laboratory in 1874 (McClellan and Dorn, 2015: 344-348). However, by now science-based engineering has become a pervasive feature of all socio-technical systems in industrialized countries.

Despite various rhetorical promises the 250-year co-evolution of single systems, interconnected systems and industrial modernity – the First Deep Transition – has gradually intensified environmental degradation while not being able to solve recurring problems of social inequality. Kanger and Schot (2019) argue that this 'double challenge' created by the First Deep Transition cannot be solved within its own boundaries. Support for new niches, transitions in single systems and investments in a new great surge of development need to be combined with the transformation of industrial modernity – collectively amounting to the Second Deep Transition – in order to direct various socio-technical systems onto sustainable and just path of development. The seeds of such change can be detected from the 1960s as a historical undercurrent. For example, in different ways the notions of appropriate technology (Schumacher, 1973), flexible specialization, post-Fordism (Piore and Sabel, 1984; Hirst and Zeitlin, 1991) or 'design global, produce local' thinking (Kostakis et al., 2015) have presented alternatives to the dominant unsustainable paradigm of mass production and mass consumption. Fig. 1 summarizes the main ideas of the framework.

[1] These are: 1) The Industrial Revolution (1771); 2) Age of Steam and Railways (1829); 3) Age of Steel, Electricity and Heavy Engineering (1875); 4) Age of Oil, the Automobile and Mass Production (1908); 5) Age of Information and Telecommunications (1971) (Perez, 2010).

Empirical exploration of the DT framework has just begun. The surge-based model by Schot and Kanger (2018) has been shown to characterize the historical evolution of rules underpinning mass production (Kanger and Sillak, 2020; Kanger et al., 2022a). Johnstone and McLeish (2020, 2022) have studied the role of World War II as a turning point event, shaping transitions in energy, mobility and food systems. Kanger et al. (2022b) have measured the continuities and ruptures in industrial modernity, finding evidence of major ideational shifts from the 1960s, and institutional shifts from the 1980s, but fairly little changes in practices. A critical appraisal has been undertaken by Erik van der Vleuten who argues that so far the DT framework has primarily focused on broad patterns of multi-system co-evolution while downplaying the role of specific actors. He suggests that more attention should be paid to the role of 'system entanglers' in connecting transitions across sector borders and creating both cross-regional similarities and differences between systems (van der Vleuten, 2019, 2020). Responding to these concerns, recent DT studies have started to pay explicit attention to such actors, e.g. Kern et al. (2020) demonstrating the instrumental role of the European Union as an international intermediary in promoting meta-rules related to circular economy, or Groß et al. (2022) highlighting the importance of transnational organizations in driving France's petroleum dependency after WWII.

Despite these recent advances the spatial dimension of Deep Transitions remains largely neglected, in terms of broad structural patterns as well as the role of actors in creating them (Smolander, 2019; van der Vleuten 2019). This makes the current DT framework unable to explain (1) how socio-technical systems emerge in, gravitate towards, become linked in and disperse from certain locations; (2) how global constraints condition actors' responses in specific geographical locations and how these responses, in turn, reproduce or transform socio-technical systems, and; (3) how these processes gradually accumulate into socio-material landscapes, posing locationally varying constraints to major transformative change. The purpose of the rest of the paper is to formulate such an explanation.

3. Spatial dynamics of technological change: seven stylized facts

In order to develop a spatial theory of Deep Transitions it is useful to begin from key observations on the spatial aspects of socio-technical change,[2] cross-cutting multiple disciplines which, however, are often characterized by very different metatheoretical commitments, theoretical frameworks, conceptual vocabulary and methodological approaches. Although at first glance this approach may raise concerns about incommensurability, it has been argued that "battles among research traditions recur not because of hardened differences over substantive issues but over preexisting epistemic convictions about what kinds of social phenomena are amenable to social analysis, what kinds of questions are important to ask, and what kinds of processes and mechanisms are most likely to be relevant" (Sil and Katzenstein, 2010: 413). For this reason "it may be possible to temporarily separate metatheoretical postulates from specific substantive claims or interpretations so as to enable direct comparison between, and greater integration across, the entire range of causal stories that aim to address similar or related empirical phenomena" (ibid.: 415). From the perspective of analytic eclecticism the recurrence of certain insights across otherwise very different schools of thought therefore serves as a source of strength as it effectively indicates the existence of a common ground[3]. In other words, such observations serve as a solid empirical foundation that an attempt to build a spatial theory of Deep Transitions cannot ignore.

In what follows these insights will be summarized as seven stylized facts (SF). In order to underscore their broad reach, the description of each includes examples from several disciplines and related empirical studies. It will also be shown how each insight has been currently embraced in the sustainability transitions field.

SF1. The spatial origins of technological, organizational, institutional, social and cultural innovations are often highly varied with actors in different locations coming up with similar solutions fairly independently of each other. Furthermore, these innovations are not restricted to a few 'leading' locations but can include both developed and developing regions (Arnold, 2005; Eder, 2019). The differing origins of scientific discoveries and technologies were already noted by sociologists in the 1920s (Ogburn and Thomas, 1922) and have been a frequently stressed by historians of technology: see, for example, Hughes (1983) on electrification and Winston (1998) on communication. Although not necessarily stressed as such, the geographical diversity of niche solutions has been recognized in the transitions field from the very first studies, e.g. Geels (2005: 205) noting that ideas about turbojets emerged independently from the work of Frank Whittle in Britain, and Hans von Ohain and Herbert Wagner in Germany.

SF2. Some places excel not only in the creation of novelty but also in 'borrowing' inventions made elsewhere and aligning them into novel configurations. The identification of factors driving the innovativeness of certain locations goes back to the pioneering works of an economist Alfred Marshall (1920). For geographers of innovation "it has become a truism that agglomeration and spatial proximity are critical for innovation" (Coenen and Morgan, 2019: 14). Historically, such places have often been large cities such as Manchester at the beginning of the Industrial Revolution (Stearns, 2013) and Berlin, New York and Boston during the 3rd surge (Hall and Preston, 1988), or city-regions such as Silicon Valley during the 5th surge (Feldman and Kogler, 2010). The locational advantages of specific areas have been extensively studied by various territorial innovation models (Moulaert and Sekia, 2003), including innovative milieux (Maillat, 1998), systems of innovation (Freeman, 1987; Asheim et al., 2011), and new industrial spaces (Saxenian,

[2] This label is explicitly chosen to indicate a broader disciplinary coverage than implied by 'geography of innovation' or other similar terms. As such the 'spatial aspects of socio-technical change' embrace: 1) not only technological but also organizational, institutional, social and cultural innovation; 2) insights related to both emerging and established solutions, e.g. technological innovations and mature technologies; 3) work from scholars who may not self-identify as geographers.

[3] A similar approach (although not explicitly labelled as such) was pursued by Kanger and Schot when they conceptualized the main features of industrial modernity through a selective synthesis of insights from various fields, including Science, Technology and Innovation Studies, history of technology, macro-sociology and socio-ecology (2019: 10-11).

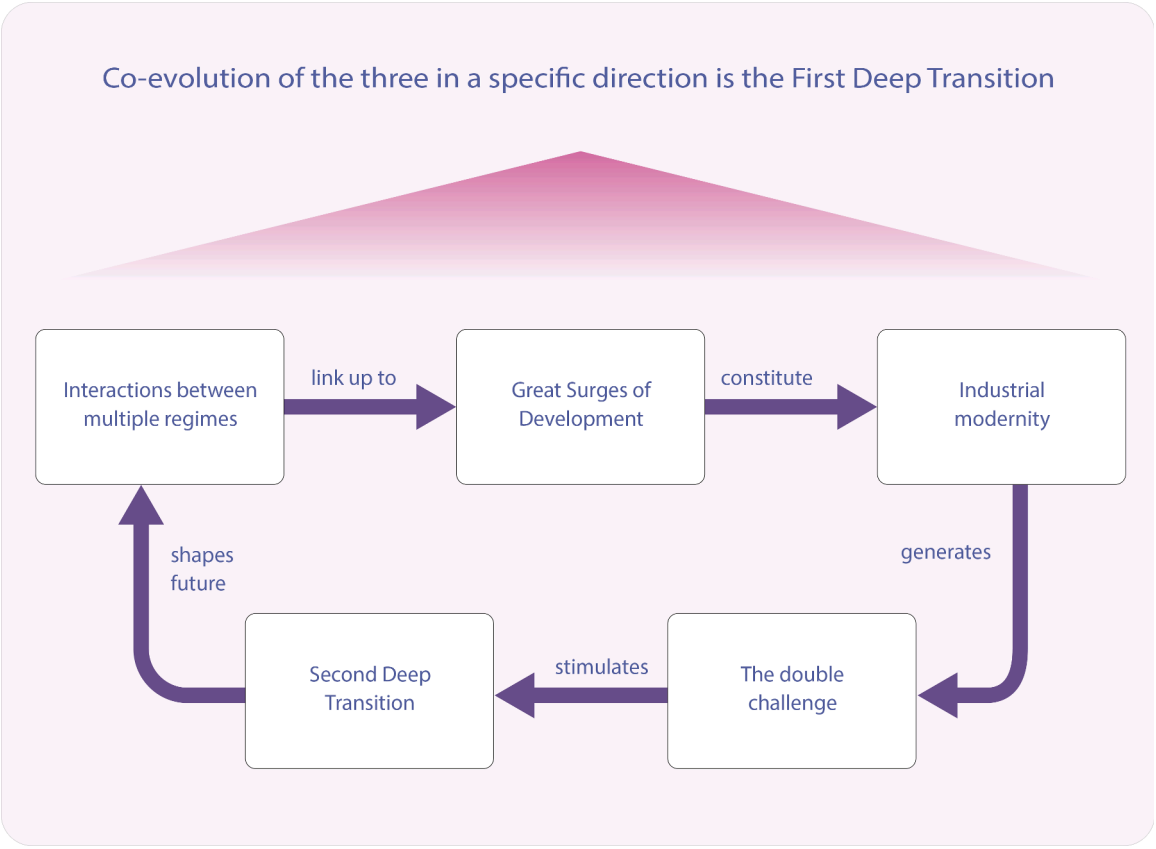


Fig. 1. The dynamics of Deep Transitions (Kanger and Schot, 2019: 18).

1994). Of those, the Technological Innovation Systems approach has become one of the core theoretical frameworks in transitions studies (Köhler et al., 2019: 4). For example, Hekkert and Negro (2009) have used TIS to analyse the build-up of biomass innovation systems in Germany and the Netherlands, detecting an alternation of virtuous and vicious cycles.

SF3. Technological, organizational, institutional, social and cultural innovations as well as their configurations travel by diffusing from innovation centres to other locations. Literature on the diffusion of innovations (Hägerstrand, 1967; Rogers, 2003; Meade and Islam, 2006; Stoneman and Battisti, 2010) focuses on identifying the determinants of this process. For example, Comin et al. (2012) find that the diffusion time tends to increase with the distance between adoption leader and the adopting country. A somewhat broader view has been adopted by evolutionary economic geographers stressing the importance of both geographical and non-geographical forms of proximity (i.e. cognitive, organizational, social, institutional) in facilitating the take-up of new ideas (Boschma, 2005; Balland et al., 2014; Davids and Frenken, 2018). This has been confirmed by historians of industrialization. For example, Stearns (2013: 53) argues that early industrializing countries were all either geographically, historically or culturally close to Britain. Sustainability transitions scholars have additionally observed that the salience of different forms of proximity varies over time: in a recent study of Italian biofuel niche Lopolito et al. (2022) found that social proximity was relevant from early on, whereas cognitive and institutional proximity only gained relevance in the maturity phase. Other scholars in the field have taken interest in transformative innovations, arguing that they diffuse through five mechanisms (growing, partnering, instrumentalizing, replicating, embedding) and result in translocally shared activities, objects and ideas (Loorbach et al., 2020).

SF4. *Actors in various locations selectively adapt and modify innovations introduced elsewhere, resulting in novel uses and designs.* Whereas diffusion literature frequently conveys the impression that technological and non-technological innovations travel through imitative learning, this assumption has been problematized by numerous detailed case studies in Science and Technology Studies, innovation studies and history of technology. For example, Kline and Pinch (1996) document how farmers redeployed first mass produced Ford Model T-s as tractors during World War I. Sustained local adaptation, in turn, can lead to distinctive outcomes as in the case of Danish wind energy in the 1970s: whereas NASA had already built large-scale prototypes in the USA, Danish actors chose to focus on the development of widely scattered small-scale wind turbines instead. This ultimately led Denmark to world leadership in wind energy (Oldenziel and Hård, 2013: 267-270). In sustainability transitions studies these insights have been used to highlight the creative role of users, e.g. the typology by Schot et al. (2016) distinguishing between user-producers, user-legitimators, user-intermediaries, user-citizens, and user-consumers.

SF5. *The likelihood of regional diversification is dependent on the types of activities already present in the area.* A steady stream of work in

evolutionary economic geography has demonstrated that technological change is place-dependent leading mostly to the accumulation of related variety rather than unrelated variety (Frenken et al., 2007; Boschma, 2021). For example, regional possibilities to specialize in green technologies are strongly conditioned by the presence of related green activities in the region and the absence of specialization to 'dirty' technologies (Santoalha and Boschma, 2021). Rapidly growing literature on the geography of transitions (e.g. Coenen et al., 2012; Truffer and Coenen, 2012; Murphy, 2015) has also started to stress place-specific factors. In an influential overview Hansen and Coenen (2015) highlight the role of local technological and industrial specialization, natural resource endowments, urban and regional visions and policies, informal localized institutions, and market-forming consumers in shaping the possibilities for sustainability transitions in particular locations. Apart from identifying factors reinforcing place-dependency, evolutionary economic geographers have also studied the conditions in which 'windows of locational opportunity' are opened up for both leading and lagging locations (Boschma, 1997, 1999). Regional R&D infrastructure, presence of key enabling technologies and country's level of development have all been shown to increase the possibility of unrelated diversification (Montresor and Quatraro, 2017; Xiao et al., 2018; Pinheiro et al., 2021).

SF6. *Innovation is a multi-scalar process, involving impacts from lower to higher scales and vice versa.* Although vigorous debates around methodological nationalism, political economy of scale and scale construction have been held in human geography since the 1990s (e.g. Smith, 1993; Brenner, 2001; Swyngedouw, 2004; Moore, 2008), multi-scalar approaches to the study of socio-technical change have started to appear fairly recently. Interactions between local, regional, national and international have been used to explain institutional change (Hermelin and Persson, 2021), social innovation (Kazepov et al., 2019) as well as the co-evolution of industries and institutions (Gong and Hassink, 2019). In sustainability transitions studies Kanger et al. (2019) have shown that the societal embedding of radical innovations entails the construction of a transnational community which serves as an arena for mutual learning, exchange of experience, consultation and negotiation, and consensus-formation. Drawing on the neo-institutionalist World Polity school (Meyer et al., 1997; Buhari-Gulmez, 2010) Fuenfschilling and Binz (2018) have introduced the notion of 'global socio-technical regimes' to account for the role of international networks in increasing the similarity of the trajectories of socio-technical systems in various parts of the world. They also show that global regimes can considerably influence socio-technical system building in a national context, e.g. by thwarting China's attempts to enact a wastewater transition. Building on this, Miörner and Binz (2021) have proposed (de-)institutionalization and re-scaling as two complementary mechanisms through which global socio-technical regimes are formed.

A particularly interesting recent contribution comes from the intersection of transitions studies and evolutionary economic geography. Based on the distinction whether particular innovations are new to a location or new to the world and whether they operate on the level of emerging niches or incumbent regimes Boschma et al. (2017) distinguish between four trajectories of regional diversification: (1) replication (old to the world and related to existing activities in the region), i.e. developing related regional industries by adopting technologies already institutionalized in the global regime; (2) transplantation (old to the world but unrelated to existing activities in the region), e.g. Brazil shifting to computer production in the 1970s despite having no local expertise in the knowledge base underpinning this regime; (3) exaptation (new to the world but related to existing activities in the region), e.g. Silicon Valley shifting from information technology to a related niche of self-driving cars; (4) saltation (new to the world and unrelated to existing activities in the region), e.g. Danish regions specialized in agriculture shifting to an unrelated niche of wind turbine production (see Table 1). In section 4 this typology will be connected to the dynamics of Deep Transitions.

SF7. *Industrialization remains an ongoing process, characterized by core-periphery dynamics.* Literature on underdevelopment and world-systems (Frank, 1967; Wallerstein, 1974-2011) has long argued that the build-up of the modern world-economy from the 'long 16th century' has been characterized by a gradually expanding core-semiperiphery-periphery structure which, however, involves a lot of ascent: states moving from the periphery to the semiperiphery and from the semiperiphery to the core (Sanderson, 2005). In innovation studies this distinction has been used by Grübler (2003) who distinguishes between core and 'rim' countries for each long wave, showing how the number of countries included in either increases from one wave to another. Similarly Perez (2010) has identified the 'leading countries' for each surge while acknowledging that changes in relative position do occur: for example, Great Britain was the leader of surges 1 and 2, whereas the third was led by Germany and USA (see Table 2 for a comparison). A less state-centric perspective has been adopted by human geographers and sociologists showing that the notion of core can also include sub-national locations, e.g. the centres of global cities (Sassen, 2002) may have much more in common with each other than their immediate surroundings (Castells, 2000-2004). These themes are echoed by recent works in transitions studies, e.g. Munro (2019) using a multi-scalar framework to study the core-periphery dynamics in Scottish energy transition, or Tirado-Herrero and Fuller (2021) calling for more attention to transitions 'from the periphery'.

The foregoing overview leads to two broad conclusions. First, the findings presented above stress the geographical circulation of a broad array of elements, including new technologies, infrastructures, industries, institutions, scientific knowledge, engineering know-how and so forth. This stands in contrast to empirical work on Deep Transitions which, to date, has primarily focused on the evolution and diffusion of rules, e.g. Johnstone and McLeish identifying four meta-rules amplified by World Wars (2022: 12), Kanger and Sillak

Table 1
Characteristics of diversification trajectories (Boschma et al., 2017: 9).

Process	Relatedness	Level	Risk	Institutional work	Key actors	Spatial logic
Replication	Related	Regime	Low	Maintenance	Regional incumbents	Localized
Transplantation	Unrelated	Regime	Moderate	Creation (especially regionally)	Regime incumbents/ governments	Global to regional
Exaptation	Related	Niche	Moderate	Creation (especially globally)	New entrants	Regional to global
Saltation	Unrelated	Niche	High	Creation (all levels)	Broad range	Global to global

Table 2
The core-rim structure of industrialized countries (Grübler, 2003: 123; Perez, 2010: 190).

Grübler		Perez	
Time	Core and rim countries	Time	Leading countries
1750-1820	**Core:** England **Rim:** Belgium, France	I surge: 1771	Britain
1800-1870	**Core:** England, Belgium **Rim:** France, Germany, USA	II surge: 1829	Britain (spreading to Europe and USA)
1850-1940	**Core:** England, Benelux, France, Germany, USA **Rim:** Central Europe, Italy, Scandinavia, Canada, Japan, Australia, New Zealand (JANZ), Russia	III surge: 1875	USA and Germany forging ahead and overtaking Britain
1920-2000	**Core:** USA, Canada, JANZ, EC-6, England **Rim:** USSR, Central and Eastern Europe, Southern Europe	IV surge: 1908	USA (with Germany at first vying for world leadership), later spreading to Europe
1980-...	**Core:** OECD **Rim:** Asian Tigers, Russia, Eastern Europe	V surge: 1971	USA (spreading to Europe and Asia)

analysing the 200-year evolution of mass production meta-regime in terms of 26 co-evolving meta-rules (2020: 7), or Kern et al. decomposing the circular economy meta-regime into four underpinning meta-rules (2020: 177). This suggests that the DT perspective might benefit from expanding its current scope of analysis, paying attention to the simultaneous circulation and alignment of rules (e.g. informal and formal institutions), objects (e.g. technologies, infrastructures, natural resources, materials) and ideas (e.g. tacit and codified knowledge, ideologies, cultural symbols).

Second, save for a few exceptions (e.g. Boschma, 1999; Grübler, 2003) the studies reviewed above have mostly focused on particular industrial activities, single technologies or, at most, single socio-technical systems. It is therefore unclear how these findings can be extended to the study of multi-system co-evolution. Furthermore, on their own the above observations remain fragmented and do not add up to a coherent framework. Therefore, the key challenge is to link them together into an account of the spatial co-evolutionary dynamics of single systems, interconnected systems and industrial modernity over the last 250 years. This task will be undertaken in the following section.

4. Towards a spatial theory of Deep Transitions: nine propositions

We have now established three pillars necessary for constructing the spatial theory of Deep Transitions: (1) the original conceptual vocabulary of the DT framework, developed specifically for understanding multi-system co-evolution (Section 2); (2) the critique of the DT framework, calling for a better structure-agency balance, and highlighting the neglect of the spatial dimension (Section 2); (3) commonly accepted findings on the spatial aspects of socio-technical change (Section 3). Utilizing these elements this section will formulate nine propositions on the spatial dynamics of Deep Transitions. In particular, propositions 1, 2, 4, 5 and 7 describe the evolutionary patterns within one surge, propositions 3 and 6 focus on actor-enacted mechanisms within one surge, whereas propositions 8 and 9 cover broader between-surge patterns. Table 3 provides a brief overview of the main ways in which the stylized facts have influenced the formation of particular theoretical propositions.

Before proceeding two qualifications should be made. First, because of DT's multi-disciplinary roots, the goal to create a middle-range theory of the spatial dynamics of Deep Transitions and the adoption of analytical eclecticism as a theorizing strategy (see Sections 1 and 2), the following propositions will be compatible with quite different understandings of space and scale. This includes acknowledging the material and discursive dimensions of scale, understanding scale as an inherited structure which, at the same time, remains an emergent socio-political project, or attention to both vertical (top-down, bottom-up) and horizontal (networked) spatial dynamics (see Brenner, 2001; MacKinnon, 2010). Hence the aim of the following is not to position the paper firmly in one meta-theoretical camp or another, but to make use of the insights of different traditions insofar as they enable to conceptualize the spatial dimension of long-term multi-system co-evolution.

Second, the section will provide various historical examples with the 4th great surge of development (Age of Oil, the Automobile and Mass Production, 1908) as its focal point. Similarly to previous outlines of the DT theory (Schot and Kanger, 2018; Kanger and Schot, 2019) the aim is not to provide a full-length empirical confirmation of the theory – this task can only be undertaken in a separate paper – but to facilitate a better understanding of the propositions on offer. However, the 4th surge has been chosen for a specific reason: namely, because it covers the existence of the Soviet Union, a superpower that aimed to present a full-scale societal alternative to the West. Hence the 4th surge enables to show that the mechanisms and patterns of multi-system co-evolution cross-cut different types of societies: planned and market economies, democratic and authoritarian states, individualist and collectivist cultures.

P1. During gestation actors in different locations experiment with multiple objects, rules for applying them and ideas legitimating their use that circulate internationally. For example, one of the major rules underlying mass production – 'make parts interchangeable' – can be traced back to the 18th century armoury town Saint-Etienne in France (Alder, 1997). During the first half of the 19th century this principle was transferred to the USA by Thomas Jefferson, French military experts and various books with the Springfield and Harpers Ferry armouries in Massachussets and Virginia as key junctions of innovation (Hounshell, 1985a). The geographical origins of rules within a country exhibit similar diversity: for example, in the USA the 'move work to worker' rule included experiments in Ogdenburg, New Jersey (Edison's iron mining facility), Cincinnati (disassembly lines in slaughterhouses), and Chicago (Western Wheel Works bicycle company using runners for parts delivery) (Hounshell, 1985a; Nye, 2013). In terms of objects, early automobile inventions in the 1880s and 1890s were largely made in Germany and France before the locus of gravity in car production shifted to the USA (McShane, 1997). From the late 19th century ideas about various forms of efficiency – technological, economic, social – started to appear in many industrialized countries (Rodgers, 1998). The need for increased efficiency and waste reduction justified the

Table 3
Correspondence between stylized facts and theoretical propositions.

Contributing stylized facts	Proposition
SF1 (Independent emergence)	P1 (Gestation)
SF2 (Locational advantages), SF5 (Place-dependence)	P2 (Installation pattern: gravitation)
SF4 (Place-specific adaptation), SF6 (Multi-scalarity)	P3 (Installation mechanisms, direction of activities)
SF2 (Locational advantages)	P4 (Turning point)
SF3 (Diffusion), SF5 (Place-dependence)	P5 (Deployment pattern: dispersion)
SF3 (Diffusion), SF4 (Place-specific adaptation), SF6 (Multi-scalarity)	P6 (Deployment mechanisms, direction of activities)
SF1 (Independent emergence), SF3 (Diffusion)	P7 (End of the surge)
SF7 (Core-periphery)	P8 (Landscape-formation)
SF1 (Independent emergence), SF2 (Locational advantages), SF3 (Diffusion), SF7 (Core-periphery)	P9 (Overall pattern)

development of new technologies and organizational innovations for many actors, e.g. Frederick Winslow Taylor and his Scientific Management' (Hughes, 1989: 188-203).

P2. During the installation period some locations emerge that tend to be systematically better in connecting new ideas, objects and rules into nascent meta-structures. As the term meta-structure is a novel addition to Deep Transitions vocabulary a brief conceptual detour is required to justify its deployment. Whereas the term meta-regime, used in existing DT vocabulary (Schot and Kanger, 2018; Kanger and Schot, 2019), refers to aligned rules coordinating developments across systems, Section 3 also demonstrated the geographical circulation of various types of ideational and material resources that cannot be easily subsumed under the notion of rules. The term meta-structure thus serves to denote interrelated rules, objects and ideas spanning multiple socio-technical systems. This formulation is in line with sociological structuration theory which is one of the metatheoretical building blocks of the Multi-level Perspective (Geels and Schot, 2010: 42-52), itself part of the Deep Transitions framework (see Schot and Kanger, 2018: 1053-1054). In an influential conceptualization Giddens (1984) proposed that structure consists of rules and resources. Building on this argument Sewell (1992) further argued that (1) whereas existing structuration theory had tended to place a primary emphasis on rules, rules and resources should be treated on a more equal footing; (2) in particular, the notion of resources should cover both, symbolic and material ones. Indeed, recently some sociologists have explicitly started to talk about 'socio-technical structures' (Elder-Vass, 2017). Translated to the DT vocabulary the term meta-structure thus encompasses all three components responsible for creating similarities between a broad array of socio-technical systems: material resources (objects), symbolic resources (ideas) and rules. Therefore, in the following meta-structure is used a more expansive notion of which meta-regime is a part.

The emergence of key connecting locations effectively means that various technological and non-technological innovations increasingly start to gravitate towards certain areas leading to single system transitions in some places and the gradual emergence of meta-structures. As the process entails the introduction of a great degree of novelty, either unrelated or related to existing locational knowledge base, diversification mostly occurs through saltation and exaptation pathways. A well-known case is Henry Ford's team of engineers in Highland Park plant, connecting various production principles, many of which were already well-known in the 19th century (e.g. electrification, use of single-purpose machinery, product standardization), into a distinctively novel regime of mass production, thereby paving way to the transformation of the American mobility system (Nye, 2013). This also led to a significant concentration of the automobile industry around Detroit, reflected in the fact that the population of the city grew from 305,000 in 1900 to 1,837,000 in 1930 (Klepper, 2007). In the Transatlantic arena, the combination of new ideas (e.g. the rhetoric of 'simplification' associating industrial diversity with wastefulness) (Scranton, 1997), objects (e.g. oil, mechanized vehicles, machine tools, assembly lines) and rules (e.g. 'move work to worker', 'separate the planning of production from execution') started to appear in various systems (e.g. mobility, defence, food) from the 1920s and 1930s – albeit to a very different degree (Kanger and Sillak, 2020). The places contributing to this process were not restricted to the Global North though: for example, the discovery of oil in 1908 and the building of refineries in 1915 enabled Iran to embark on constructing "a small but vigorous modern industrial sector in an otherwise backward economy" (Stearns, 2013: 192).

Despite this geographical circulation and 'gravitational pull' some components of the future meta-structure are pioneered at particular locations and remain anchored there for the time being. Examples include Soviet economic and institutional experiments with highly centralized planning from the 1920s (Bailes, 1981; Link, 2020) and Nazi Germany's highway road infrastructure in the 1930s that were not widely imitated in Western Europe and USA before World War II. In other words, whereas various building blocks are being pioneered during the installation period, no location pulls all of them together and hence meta-structure building remains incomplete. This also means a high degree of uncertainty about the still-emerging meta-structure, including its envisioned areas of application, its links to other technologies, institutional frameworks and ideological discourses, and its broader societal impacts. For example, in the interwar era mass production was associated with widely divergent future promises such as sustainable resource use, abandonment of class structure and shorter working hours but also the aggravation of inequality, technological unemployment and homogenization of culture (Van Deventer, 1923; Filene, 1931; Maier, 1970; Nye, 2013).

P3. Actors respond to new opportunities through four mechanisms (imitation, selective adoption, creative modification, rejection) and share their experience in two directions (bottom-up, top-down) but in the installation period rejection/selective adoption and bottom-up activities are dominant. When encountering a novel configuration of transnationally circulating ideas, objects and rules an actor in a specific place is basically faced with four choices: (1) imitation, i.e. full-scale adoption without any modification; (2) selective adoption, i.e. choosing some elements from the configuration while discarding the rest; (3) creative modification: a rare but particularly important act of adopting the configuration but developing the existing elements, adding new ideas, objects and rules, and/or changing the linkages between the three[4]; (4) rejection: deciding against adoption altogether. The first three play a crucial role in the emergence, consolidation and circulation of the meta-structure. However, differing locational capabilities and high degree of uncertainty – characteristic features of the installation period – strongly guide most actors in most places to cling on to incumbent solutions, largely rejecting solutions deemed incompatible with local technological infrastructure, knowledge base and institutions. Even when actors do decide to experiment with new ideas, objects and rules success is far from guaranteed as novel applications might fail or actors might end up committing themselves to an evolutionary dead-end. An overall result is a high degree of spatial heterogeneity: not only do locations differ in terms of the presence of 'old' and 'new' ideas, objects and rules but also in terms of various

[4] Note that the boundaries between imitation, selective adoption and creative modification cannot be strictly drawn for even the seemingly simple act of technology adoption by households has been shown to involve a great deal of symbolic, practical and cognitive work (Lie and Sørensen, 1996). Hence the three should be rather viewed as a continuum, referring to differing degrees to which the adopter alters the originally available configuration of ideas, objects and rules.

combinations of the 'new'.

During the interwar era one can observe all four mechanisms in operation:

1 Imitation: already during World War I Ford extended mass production to food (Fordson tractors) and defence systems (largely failed attempts to produce submarine patrol boats) (Hounshell, 1985b; Nye, 2013). Over the 1920s and 1930s such extension attempts gradually started to create a common directionality in mobility, food and defence systems in the Transatlantic region, reflected in the increasing use of mechanized, mass produced and fossil fuel based vehicles. At the same time, many other attempts of direct imitation such the production of houses on assembly lines failed in both Europe and USA (Hounshell, 1985a).
2 Creative modification: in response to Ford's rigid focus on productivity maximization and price-cutting of a single product (Model T), from the mid-1920s General Motors started seeking a better balance between economies of scale offered by mass production and diversity in demand. This involved multiple technological, organizational and business model related innovations such as using similar components across different car models, customizing general-purpose machinery for particular uses, following the strategy of planned obsolescence, introducing instalment buying and adopting a multi-divisional decentralized corporate structure (Flink, 1990). The alignment of these ideas, objects and rules constituted a distinctive configuration, called 'flexible mass production' (Hounshell, 1985a).
3 Selective adoption: in Europe various attempts to apply a selective mixture of Fordist production, Taylorist management and Sloanist business practices often resulted in local variations such as Fayolism and Bedaux system in France or Bataism in Czechoslovakia (Schröter, 2007; Kohlrausch and Trischler, 2014). For example, all three major French automobile producers (Renault, Citroën, Peugeot) adopted a hybrid strategy, combining backward integration (Ford), mass production techniques (Ford and General Motors), product diversification, and the development of broader organizational capabilities (both from General Motors) (Smith, 2006: 408). The Soviet Union, in turn, introduced centralized economic planning, combining it with Fordist production and more authoritarian elements of Taylorist organization (Bailes, 1981). Extensive state intervention to economic activities was also undertaken in Nazi Germany (Temin, 1991; Landes, 2003: 398-419). At the same time each region rejected parts of the future meta-structure. While Soviet economic planning was extensively studied by the Western countries (Hobsbawm, 1996: 96-97) attempts to implement large-scale state intervention were heavily contested in democratic countries. The Soviets, in turn, largely rejected American commercial methods and techniques of industrial management as inappropriate to a socialist country (Bailes, 1981).
4 Rejection: whereas mass production techniques continued to be adopted in various American systems, their take-up in Europe was much more limited. The combination of several factors such as the presence of a strong craft tradition, smaller national markets, lower purchasing power and consumer preference for variety often led European industrialists and politicians to reject American-style production techniques (Nye, 2013). Indirect evidence of the prevalence of rejection can also be found in the structure of national economies. For example, even in the USA as the 'leading country' of the 4th surge, specialty production still contributed about a third of value added and employment in 1923 (Scranton, 1997: 340-343).

In order to share their experience, engage in mutual learning, align expectations and standardize various components of the emerging meta-structure actors engage in various 'bottom-up' activities during the installation period. This results in the formation of new or the consolidation of existing organizations on multiple scales. For example, in 1924 American Automobile Association gathered together various local, state and national clubs becoming a single representative of motorists in the USA (Norton, 2008: 170). In Europe many semi-state institutions were set up in order to promote the rationalization of industry, e.g. the British Higher Productivity Council in the UK, the Work Efficiency Organization in Finland and Reichskuratorium für Wirtschaftlichkeit in Germany (Schröter, 2007: 219). A similar process was occurring in the transnational arena with the growing country membership of car and road organizations such as the Association Internationale des Automobile Clubs Reconnus, the Ligue Internationale des Associations Touristes or the Permanent International Association of Road Congresses (Kanger et al., 2019).

P4. At the turning point one location manages to link various ideas, objects and rules into a dominant meta-structure that sets a paradigmatic example, a 'global template' for other places. In many ways World War II helped to accelerate developments already underway in USA. By greatly increasing the need for standardized products in existing and new domains (e.g. uniforms, food, cars, tanks, airplanes) WWII prompted government procurement, international agreements (e.g. the Lend Lease Act) and state investments in factories. All this created a productive capacity that could be converted for civil purposes after the war (Nye, 2013). The forced savings of a substantial amount of soldiers (Gordon, 2016), in turn, enabled post-war mass consumption. Wartime conditions also heightened the need for 'mass loyalty' which meant putting labour conflict on hold and mobilizing the entire population in the name of cooperation and shared sacrifice (Nye, 2013: 128-131; Johnstone and McLeish, 2022). This legitimated large-scale state intervention in economic activities and signalled the possibility of a post-war welfare state.

However, while promoting meta-structure consolidation in some locations, WWII also served to close off alternative directionalities in other ones. For example, in the 1930s the production of biogas from waste and wastewater was widely practised in Germany, with methane gas stations for vehicles operating in Stuttgart, Halle, Pforzheim, Essen, Erfurt, Pößneck and Munich. However, as these technologies were strongly associated with the Nazi regime, they became a liability in post-WWII era, were deliberately ignored during successive decades, and re-emerged only in the 2000s (Moss, 2017).

P5. During the deployment period the dominant meta-structure disperses from the core location to other ones where interactions between the 'global template' and local place-specificities result in locational varieties of the meta-structure. The presence of a 'global template' reduces uncertainty, creates considerable isomorphic pressures and thereby leads to the reduction of spatial heterogeneity. Actors' ability to build on already existing transnational experience means that locational diversification now mostly occurs through

transplantation and replication pathways. At the same time place-specific factors (e.g. local industries, knowledge base, availability of capital, public attitudes etc.) continue to shape the extent to which the dominant meta-structure is adapted. As a result, while socio-technical systems in different places become somewhat more similar to each other in terms of shared ideas, objects and rules, notable differences prevail.

The post-war meta-structure united a number of ideas (e.g. belief in post-war reconstruction of Europe as a key to peace, perception of the nation state as a default unit of economic activity, notion of societal progress through material abundance), objects (e.g. oil, mass production technologies, cheap and widely accessible consumer goods), and rules (e.g. the imperative to adopt a vertically integrated and multi-divisional corporate structure, institutionalization of a social contract between employers, labour and state) (Freeman and Louçã, 2001; Trentmann, 2016). This meta-structure manifested itself in particular links between systems, e.g. mobility-housing (e.g. car-based lifestyles promoting urban sprawl), or energy-food (abundance of oil enabling intensive agriculture). From the 1950s American-style production techniques, corporate organization structures, management styles, distribution techniques, advertising and consumer goods started to flood to the Transatlantic region (Schröter, 2007). Importantly, this meta-structure affected countries which had set itself up in opposition to the West as well as countries in the Global South. For example, Soviet 'consumer socialism' explicitly aimed to match USA in housing and consumer durables (Castillo, 2005), whereas industrialization in Brazil involved a rapid growth of the country's automobile industry (Kohli, 2004). This asymmetrical geographical influence is commonly captured by the term 'Americanization' although authors differ in their emphasis on either cross-regional similarities (Schröter, 2007) or differences (Zeitlin and Herrigel, 2000).

P6. Although actors continue to respond to the dominant meta-structure through four mechanisms and share their experience in two directions in the deployment period imitation/selective adoption and top-down activities are dominant. As the structural conditions have changed the same actor-enacted mechanisms now play out in a different manner. The key question of the installation period – 'whether to adopt' – now increasingly turns into 'how'. The two logics are decisively different: whereas the combination of rejection and selective adoption in the installation period often leads to "be cautious and adopt as little as possible", the combination of imitation and selective adoption in the deployment period manifests itself as "start from the global template, deviate where necessary".

Another important contextual difference is the existence of a consolidated transnational community, creating powerful top-down channels of influence. As such actors in a broad range of locations are now strongly inclined to adopt the dominant meta-structure, drawing inspiration on how it is being applied in the core. Well-known examples include the Marshall Plan, the Productivity Mission, Fulbright Program and United States Information Agency which mediated the American experience to the entire Transatlantic region. Top-down influence was also channelled through newly established transnational organizations, e.g. the role of the International Road Federation in promoting road-building for mobility systems in developed and developing countries (Mom, 2020), or the Food and Agricultural Organization in propagating intensive agriculture for food systems (Barton, 2018).

A recent study of the making of France's petroleum dependency between 1948 and 1975 (Groß et al., 2022) provides a rich illustration of complex connections between multi-scalar agency, multi-site impacts and multi-system co-evolution. It shows how transnational actors, especially the Organization for European Economic Co-operation, incentivized France to build up its oil refining capacities, stimulating, in turn, the exploration of oil fields in Africa and Middle East. This resulted in a transnational business network, connecting oil elites in Metropolitan France to decolonizing African nations. The refinery output itself then facilitated the co-transition of French energy, mobility and food systems, effectively locking the country onto an energy- and material-intensive path of development.

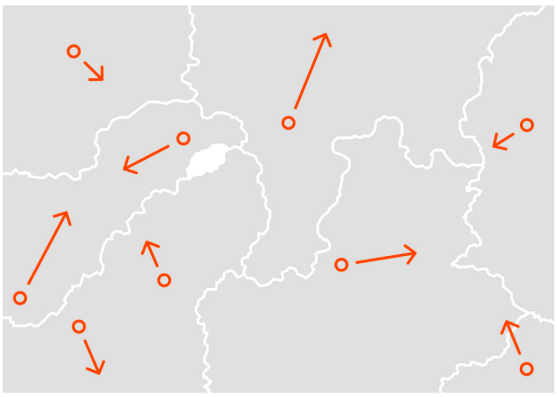
Whereas creative modification is exceedingly rare the continuing importance of this mechanism cannot be understated. Japan is a case in point. In 1948 Toyota started to experiment with various improvements to American-style mass production, including just-in-time supply provision, stopping work upon spotting an error, or using worker expertise as an input for production improvement. By the 1960s the lessons of various Japanese companies started to coalesce into a distinctive variation of production organization later called 'lean production' in the West (Krafcik, 1988; Holweg, 2007). Importantly, these changes were originally introduced as a response to constraints that had made Europeans largely reject mass production in the interwar era – relative lack of capital, smaller volumes of production and higher variety of models. This illustrates that the nature of locational responses does matter for the outcome – in this particular case enabling Japanese cars to achieve superior cost competitiveness, quality and reliability which, in turn, was reflected in increasing global market share (Tolliday and Zeitlin, 1988). Table 4 summarizes the main differences between installation and deployment periods.

P7. The end of the surge is characterized by three parallel processes: gradual decoupling of linkages in the dominant meta-

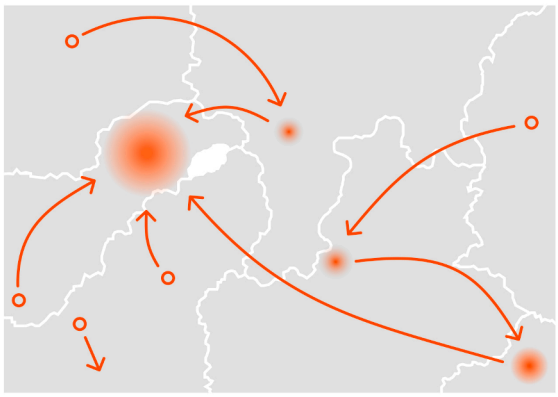
Table 4
Comparison of installation and deployment periods.

	Installation	Deployment
Uncertainty	High (but gradually decreasing)	Low (but increasing towards the end of the surge)
Main spatial pattern	Gravitation	Dispersion
Dominant pathways of locational diversification	Saltation, exaptation	Replication, transplantation
Degree of spatial heterogeneity	Higher	Lower
Dominant mechanisms	Rejection and selective adoption: to adopt or not to adopt?	Imitation and selective adoption: how to adopt?
Dominant direction of activities	Bottom-up: creating a transnational community	Top-down: influence from a transnational community

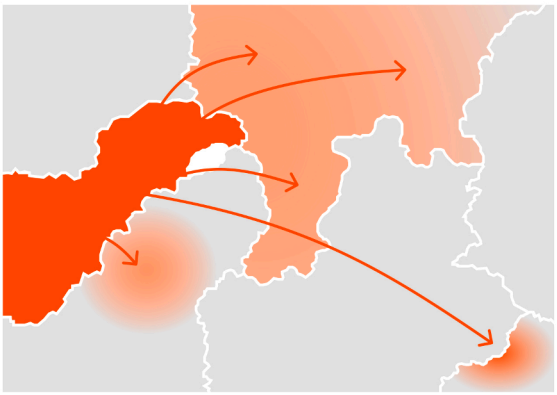
structure, the continued spread of specific elements of this meta-structure, and the emergence and gradual alignment of the elements of the next surge in various geographical niches. The maturation of the dominant meta-structure results in its increasing contestation on economic, political, cultural and environmental grounds, e.g. the emergence of an increasingly transnational environmental movement from the 1970s (Warde et al., 2018). In the context of increased uncertainty the configuration of dominant ideas, rules and objects thus starts to unravel. Somewhat paradoxically, this very decoupling might serve as an additional stimulus for the further dispersion of some elements of the formerly dominant meta-structure. For example, corresponding to profitability concerns American enterprises gradually started to offshore manufacturing jobs from the 1960s (Ericson, 1970). This unleashed a process of rapidly escalating deindustrialization and regional deprivation: between 1978 and 1982 the USA lost 300,000 jobs in the automobile industry, 85,000 of those in Detroit (Dicken, 1986, quoted in High, 2021: 170). For the developing countries, however, offshoring created



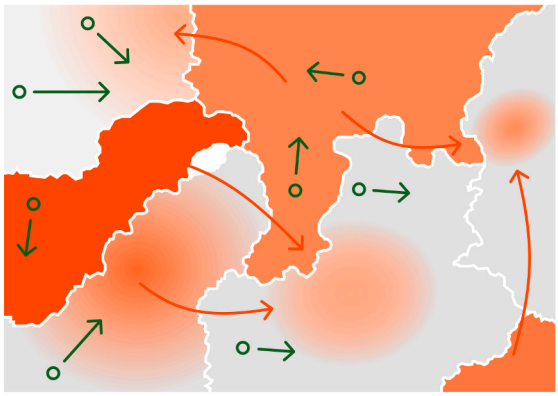
Gestation: actors in different locations experiment with new objects, rules for applying them and ideas legitimating them that circulate internationally **(P1)**.



Installation: some places are better in aligning new ideas, objects and rules and ideas into nascent meta-structures. In general rejection, selective adoption and bottom-up activities dominate, leading to highly varying locational outcomes **(P2, P3).**



Turning point/deployment: one location defines the meta-structure **(P4)** that starts to disperse to other ones **(P5)**. Imitation, selective adoption and top-down activities now dominate resulting in locational varieties of the meta-structure **(P6)**.



Onward from late deployment: decoupled spread of the formerly dominant meta-structure, experiments with the elements of the new surge in geographical niches **(P7)**. Industrial modernity accumulates from one surge to another but with locational variety **(P8)**. Taken together P1-P8 generate a distinctive spatial pattern **(P9)**.

Fig. 2. The spatial dynamics of Deep Transitions.
Note: in order to stress more clearly that the model is meant to be applicable beyond specific surges and their associated spatial constellations, the Fig. is based on a fictional map.

additional opportunities to shift to new industrial activities, eventually resulting in a new international division of labour (Fröbel et al., 1980; Milanovic, 2016). Offshoring also meant decoupling mass production from the assumption of nation state as the default unit of economic activity and introducing a geographical divide between producers and end users – connections that had been central to post-war growth in the entire Transatlantic region.

In parallel, various innovations had been gestating for a while, including wartime breakthroughs in electronic computing (Z3 in Germany, Colossus in UK and ENIAC in USA), experiments with production automation from the 1950s (led by USA, but also including Germany, France and USSR), networking (ARPANET in USA, various failed attempts in USSR) and 'lean' management (Japan) (Winston, 1998; Abbate, 1999; Nye, 2013; Peters, 2016). From the 1970s, attempts at neo-liberal state reform (Chile, UK, USA) were added to the picture (Harvey, 2006), enabling a new wave of globalization and the associated rise of multi-national corporations. All these elements gradually came together over the following decades, constituting a new dominant meta-structure of the 5th surge.

P8. Through successive surges the multi-scalar dynamics of gravitation and dispersion lead to the accumulation of the socio-material landscape of industrial modernity, but with distinctive locational varieties. As argued in Kanger and Schot (2019) industrial modernity refers to as a set of most durable and expansive features of industrial societies, introduced during specific surges but retained and reinforced during the following ones. From the spatial perspective industrial modernity can be thought of as a socio-material landscape with five layers – 'imprints' left by each surge (Johnstone and McLeish, 2022) – and with each layer, in turn, consisting of some ideas, objects and rules. The interplay between global isomorphic and place-specific features means that locations differ in the extent to which they absorb the ideas, objects and rules related to a particular surge. Extending this line of reasoning to a succession of surges one can therefore propose that over time places come to exhibit variation in the extent to which they embed the fundamental ideas, objects and rules of industrial modernity. Despite these locational differences, on an aggregate level the socio-material landscape of industrial modernity continues the process of gradual accumulation all over the globe as the number of locations belonging to the core increases.

Such locational variation can be demonstrated through a country level comparison of two important features of industrial modernity, one related to prevalent ideas and one to material objects: belief in techno-scientific progress and dependence on resource-intensive socio-technical systems (Kanger and Schot, 2019: 12). In relation to the former, only 15% of Dutch people strongly agree (9 and 10 on a 10-point scale) with the claim that the world is better off because of science and technology, whereas 32.1% of Americans and 32.5% of Germans do so (World Values Survey, 2020). In relation to the latter, the number of vehicles per 1000 people is 499 in the Netherlands and 574 in Germany, but remarkably higher, 836, in the USA (Davis and Boundy, 2021: 3-12; Eurostat 2020). Yet all the three countries industrialized early, had gained a core status by the beginning of the 20th century (see Table 2), and benefited massively from the 4th surge in terms of mass-produced cars, abundant consumer durables, economic growth, and societal welfare. Emerging empirical evidence also shows that these differences have deep historical roots: in a comparative study of Australia, Germany and Soviet Union/Russia between 1900 and 2020 Kanger et al. (2022b) find lasting differences in public discourse, institutions and practices related to the natural environment, technology and innovation.

The deployment period of the 4th surge provides a dramatic example of the cumulative impacts of landscape-formation. In decades following WWII the mass production/consumption paradigm became globalized (Kanger and Sillak, 2020), intensifying the associated general features of industrial modernity, e.g. instrumental view of nature, belief in limitless availability of resources, or the anticipation of an ever-increasing number of goods for lower prices (Kanger and Schot, 2019: 12). The sheer number of locations involved in this process resulted in the Great Acceleration of numerous Earth system and socio-economic trends from the 1950s (McNeill and Engelke, 2014; Steffen et al., 2015), including increases in material flows, water use and waste generation (Krausmann et al., 2018; Haberl et al., 2019) coupled with a decrease in circularity (Haas et al., 2020). The lasting legacy of this process is well illustrated by the fact that recently global human-made mass exceeded all living biomass for the first time in history (Elhacham et al., 2020).

P9. *Overall, various forces described in previous propositions generate a specific long-term spatial pattern.* Propositions 1-8 have described four processes: (1) gravitation of ideas, objects and rules towards certain locations in the installation period; (2) dispersion of a dominant meta-structure from the core area in the deployment period; (3) continued dispersion of elements of the formerly dominant meta-structure during successive surges; (4) gradual but place-dependent accumulation of industrial modernity in various places. Figuratively speaking, over 250 years one may thus imagine each surge as a pulsating centre (gravitation during installation, dispersion during deployment) with ripples spreading outwards (continued global dispersion during the next surge), and an expanding surface area (corresponding to the gradual increase of locations adopting the meta-structure of industrial modernity). Fig. 2 visualizes the entire model.

5. Conclusion

This paper has provided the first sketch of a spatial theory of Deep Transitions. Owing to the enormity of the task this endeavour has been necessarily incomplete and there can be no doubt that, depending on their disciplinary backgrounds, different readers will find much to quarrel with. Hence rather than wrestling against unrealistic expectations of perfection at the first attempt, this paper has settled on a somewhat more modest ambition aiming to exhibit three qualities: (1) novelty, i.e. offering a new explanation of the spatial patterns, mechanisms and cumulative outcomes of multi-system co-evolution over a 250-year time-frame; (2) plausibility, reflected in the internal coherence of the nine propositions which do not err against established knowledge on the spatial aspects of socio-technical change; (3) interestingness, that is, challenging some core assumptions of the reader and inviting further research in order to confirm, refine, amend or undermine the propositions on offer. If all else fails, it is hoped that the paper could at least turn out to be productively wrong.

If, however, the DT framework is any good, its propositions strongly imply a need for a fundamental overhaul in a broad range of

socio-technical systems underpinning industrial societies to respond to the double challenge of environmental degradation and social inequality. So how does the socio-spatial legacy of the First Deep Transition shape the possible emergence of the Second Deep Transition? And what research avenues does the spatial theory of DT suggest to pursue in this regard? To answer these questions, the paper will conclude with a brief research agenda, focusing on four promising topics: cities, geographical hotspots for the Second Deep Transition, learning from the Global South, and landscape-shaping technologies.

First, the spatial perspective highlights the important role of cities in the First Deep Transition. However, as urban population is expected to reach 60% by 2030 (UNDESA, 2018) cities are now increasingly seen as crucial sustainability hubs (Hodson and Marvin, 2010; Frantzeskaki et al., 2017; Short and Farmer, 2021) with some scholars going as far as to argue that they will replace nation-states as key players in the global arena (Brenner, 2004; Castells, 2000-2004). If this is indeed the case, it opens up an intriguing possibility that – contrary to the surges of the First Deep Transition characterized by one dominant core location (see Table 2) – the Second Deep Transition might be poly-centric instead. What is the capability of cities to go beyond experimentation, and to connect various types of innovations into sustainable and just meta-structures? And what will the corresponding spatial pattern of innovation centres and peripheries look like?

Second, the spatial theory directs attention to the uneven distribution of the socio-material landscape of industrial modernity. This means that the opportunities for enacting the Second Deep Transition vary considerably between different locations. Here DT's simultaneous attention to ideas, objects and rules promises to go beyond the reproduction of Global North/South divide in many existing measurements, e.g. the North coming out on top in Human Development Index and Global Innovation Index (UNDP (United Nations Development Programme) 2020; WIPO (World Intellectual Property Organization) 2020), and the South dominating the 'safe and just space' rankings and the Sustainable Development Index (O'Neill et al., 2018; Hickel, 2020). However, many countries in the Global North, currently dominated by resource-intensive socio-technical systems, may also be characterized by supportive public attitudes and transformative institutions to change this situation. On the other hand, in many countries in the Global South the current low resource use may be amply offset by beliefs in the primacy of economic growth and lax environmental regulations (Xing and Kolstad, 2002), driving industrialization at all costs. So where do the combined ideas, objects and rules of industrial modernity currently pose the least constraints? Where do we observe the spatial clustering of technological, organizational, institutional, social and cultural niche innovations with high transformative potential? If the theory offered in this paper is valid, the locations where the relative lack of structural constraints meets creative improvisation effectively constitute the geographical hotspots for the Second Deep Transition.

Third, the First Deep Transition generated a sharp Global North/South divide, where the former largely defined the dominant meta-structures, whereas the latter was mostly relegated to cheap resource provision and to the adoption of meta-structures. Historically this has often left the Global South with a need to address extreme forms of environmental degradation and social inequality in a creative manner, reflected in various emerging movements like rights to nature (Borràs, 2016; Pecharroman, 2018), frugal innovation (Numminen and Lund, 2017), or inclusive innovation (Onsongo and Knorringa, 2020). However, the current globalization of the double challenge means that in many ways the Global South may now find itself pre-adapted for creating a meta-structure underpinning the sixth green surge and introducing the Second Deep Transition. If this is indeed the case, it would necessitate a major reversal in the direction of global learning, with the Global North having to do much more listening than previously. How to create favourable conditions for sustained, broad and deep South-to-North knowledge transfer? And how to nurture locational capabilities for creative modification (generation of variety, aggregating nascent ideas, objects and rules into meta-structures) and appropriation (imitation, adaptation of meta-structures to local conditions) across the North/South divide?

Fourth, the First Deep Transition has been characterized by the successive expansion of the boundaries of socio-technical systems, both deeper into the Earth (Marín and Goya, 2021) and further into outer space (Yap and Truffer, 2021). The increasing scale and scope of these systems has brought bigger crises which, in turn, has led to the emergence of Earth system interventions such as solar geo-engineering (Reynolds, 2021) as possible solutions. In contrast to past niche innovations that targeted specific systems, however, these new interventions increasingly aim to directly alter the socio-ecological landscape in which the systems are situated. How does the interaction of niches within systems and innovations explicitly designed to tilt the landscape shape the formation of future meta-structures? Does the landscape level assume increasing importance in shaping multi-system interactions during the Second Deep Transition? If so, there might be an urgent need to develop novel conceptual vocabulary for speaking about the category usually considered 'residual' in transitions studies.

The maturation of the sustainability transitions field over the past decade has been coupled with the escalation, deepening and amplification of global socio-ecological crises, unfolding in front of our very eyes. This means that transitions research cannot afford to remain modest, cannot afford to become self-satisfied, and most importantly, cannot afford to shy away from big questions even if there are no good answers to be immediately found. Developing theory-guided but place-specific interventions for enacting the Second Deep Transition therefore constitutes a pressing challenge, existential in nature, daunting in difficulty yet also most rewarding in promise. One can only hope that this paper has managed to utter a first sentence in a series of fruitful future conversations.

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