Technological Forecasting & Social Change 177 (2022) 121491

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

Deep transitions: A mixed methods study of the historical evolution of mass production

Laur Kanger [a,b,*], Frédérique Bone [a], Daniele Rotolo [a,c], W. Edward Steinmueller [a], Johan Schot [d]

[a] SPRU – Science Policy Research Unit, University of Sussex Business School, Brighton BN1 9SL, United Kingdom
[b] Institute of Social Studies, University of Tartu, Lossi 36, Tartu 51003, Estonia
[c] Department of Mechanics, Mathematics and Management, Polytechnic University of Bari, Bari, Italy
[d] Centre for Global Challenges, Department of History and Art History, University of Utrecht, Janskerkhof 2-3a, Utrecht 3512 BK, the Netherland

ARTICLE INFO

Keywords:
Deep transitions
Socio-technical systems
Rules
Mass production
Mixed methods
Text mining
Historical sources

ABSTRACT

Industrial societies contain a range of socio-technical systems fulfilling functions such as the provision of energy, food, mobility, housing, healthcare, finance and communications. The recent Deep Transitions (DT) framework outlines a series of propositions on how the multi-system co-evolution over 250 years of these systems has contributed to several current social and ecological crises. Drawing on evolutionary institutionalism, the DT framework places a special emphasis on the concepts of 'rules' and 'meta-rules' as coordination mechanisms within and across socio-technical systems. In this paper, we employ a mixed-method approach to provide an empirical assessment of the propositions of the DT framework. We focus on the historical evolution of mass production from the 18th century to the present. Combining a qualitative narrative based on a synthesis of secondary historical literature with a quantitative text mining-based analysis of the corpus of *Scientific American* (1845–2019), we map the emergence and alignment of rules underpinning mass production. Our study concludes by reflecting on important methodological lessons for the application of text mining techniques to examine large-scale and long-term socio-technical dynamics.

1. Introduction

Industrial societies are underpinned by socio-technical systems fulfilling various functions like energy, food, mobility, housing, healthcare, finance, communications, education and security provision. Throughout the history of industrialization these systems have often been connected in a manner that generates or amplifies environmental problems, such as the contribution of suburbanized housing, the rise of supermarkets, and individualized mobility to greenhouse gas emissions, or the role of the finance system in maintaining the stability of fossil fuel-based energy systems. Societies all over the world are fundamentally dependant on energy- and material-intensive socio-technical systems whose growth trajectory is unsustainable – manifested in environmental degradation, loss of biodiversity and resource depletion (Steffen et al., 2015; Intergovernmental Panel on Climate Change 2018; Haberl et al., 2019).

Drawing on a broad range of insights from Science, Technology and Innovation Studies, the field of sustainability transitions has extensively studied the dynamics of socio-technical system shifts (e.g. Grin et al., 2010; van den Bergh et al., 2011; Markard et al., 2012), including an emerging stream of works on multi-system interactions (e.g. Geels, 2007; Raven and Verbong, 2007, 2009; Konrad et al., 2008; Papachristos et al., 2013; Sutherland et al., 2015; Hiteva and Watson, 2019). The need to increase our understanding of this topic has also been stressed in the new Sustainability Transitions Research Network agenda (Köhler et al., 2019: 6; Rosenbloom, 2020).

Multi-system interactions are central to the recent Deep Transitions (DT) framework (Schot and Kanger, 2018; Kanger and Schot, 2019) which aims to provide a comprehensive account of a long term transition of economies and societies. Synthesizing insights from transitions studies (Rip and Kemp, 1998; Geels, 2005; Grin et al., 2010), long wave theory (Freeman and Louçã, 2001) and industrialization literature (Landes, 2003; Stearns, 2013; Mokyr, 2017), the DT framework offers 12 propositions on the patterns and mechanisms of a 250-year multi-system co-evolution. It theorizes how interactions between socio-technical systems have resulted in 'great surges of development' of about 40–60 years (Perez, 2002), and how successive surges, in turn, have

* Corresponding author at: SPRU – Science Policy Research Unit, University of Sussex Business School, Brighton BN1 9SL, United Kingdom.
E-mail addresses: l.kanger@sussex.ac.uk (L. Kanger), f.bone@sussex.ac.uk (F. Bone), d.rotolo@sussex.ac.uk (D. Rotolo), w.e.steinmueller@sussex.ac.uk (W.E. Steinmueller), j.w.schot@uu.nl (J. Schot).

https://doi.org/10.1016/j.techfore.2022.121491
Received 25 June 2021; Received in revised form 24 November 2021; Accepted 6 January 2022
Available online 29 January 2022

accumulated into a set of most fundamental beliefs and principles underpinning industrial societies - an industrial modernity. The co-evolution of single systems, interconnected systems, and industrial modernity over the last 250 years has gradually intensified various forms of environmental degradation while not being able to solve recurring issues of social inequality in connection to unequal access to healthcare, energy, water, food, mobility, security, finance, education, and communication. Because of this common trajectory the entire process is called the First Deep Transition. Arguably, altering the directionality of the First Deep Transition requires another major shift, the Second Deep Transition. From this perspective, the key to redirecting contemporary socio-technical systems onto a sustainable and just path of development is an understanding of the historical genesis of their shared directionality.

Although the initial outline of the DT framework relied on selected illustrative historical examples, a systematic empirical exploration of the propositions of the framework is still in the early stages (see Johnstone and McLeish, 2020; Kanger and Sillak, 2020; Kern et al., 2020). Studying a phenomenon as complex as Deep Transitions requires going beyond the limitations of narrative explanations and use of secondary sources for historical case studies (Genus and Coles, 2008; Sorrell, 2018; Svensson and Nikoleris, 2018) as commonly employed in sustainability transitions literature. In this paper, we therefore focus on two research questions, one substantive and one methodological: (i) to what extent are the evolutionary patterns proposed by the Deep Transitions framework manifest in empirical data? (ii) how can the complex co-evolutionary and long-term patterns of Deep Transitions be studied?

We argue that empirical research on Deep Transitions demands pushing the methodological boundaries of sustainability transitions studies in two ways: (i) the adoption of mixed method research designs where the joint deployment of quantitative and qualitative methods complements their strengths while offsetting their mutual weaknesses (Schot and Kanger, 2018: 1057; Zolfagharian et al., 2019) and (ii) the incorporation of longitudinal textual data, largely unexplored in existing studies on long-term systems change. Our paper thus introduces a novel methodological approach that can be used to study both single system transitions and multi-system interactions, and opens up a new research avenue that offers new opportunities to scholars studying long-term systems change.

We focus on a set of propositions on the co-evolutionary patterns of the DT framework as outlined in Schot and Kanger (2018), analysing mass production as 'a most-likely case' (George and Bennett, 2005). We employ a sequential exploratory research design (Creswell and Plano Clark, 2018) where the findings of a qualitative historical case study (mass production in the Transatlantic region[1] from 1765 to the present) are used to specify inputs for the quantitative text mining analysis of two historical sources (a journal titled *Scientific American* and manuscripts brought together in *Google Books* from 1845 to 2019, with the latter primarily used for robustness analysis). The two approaches are complementary as text mining allows exploration and quantification of the timing and frequency of the dynamics described qualitatively in the historical narrative. The evolutionary patterns detected by both approaches are then compared and integrated. To our knowledge this research design is the first attempt to use textual data sources for the study of long-term socio-technical systems change and to employ text mining techniques for the exploration of a broad and complex conceptual framework. Reflecting on both the successes and limitations of this methodological approach will therefore inform scholars in the innovation studies and sustainability transitions fields seeking to make use of text mining and mixed method research designs.

The paper is organized as follows. Section 2 outlines the central concepts of DT framework – i.e. rules, meta-rules, regimes and meta-regimes – and presents a model of how interacting rules come to constitute long-term patterns. Section 3 describes our research design. Section 4 provides an overview of the results of our qualitative and quantitative research. The contextualization of these results as well as reflections on methodological limitations of the proposed approach are discussed in Section 5. Section 6 concludes the paper.

2. Theoretical framework

The DT framework focuses on two gaps in the innovation studies and sustainability transitions fields: first, establishing an explicit connection between shifts in single systems and the resulting higher-order patterns as described in transitions (Geels, 2005; Grin et al., 2010) and long wave literature (Freeman and Louçã, 2001; Perez, 2002), respectively (Schot and Kanger, 2018); second, theorizing the genesis of major historical continuities characterizing the industrialization and modernization process as a whole (Kanger and Schot, 2019). Building on evolutionary institutionalism (Fürstenberg, 2016), sociological structuration theory (Giddens, 1984; Sewell 1992) and the application of these insights in the Multi-Level Perspective (MLP) on socio-technical transitions (Geels, 2004; Geels and Schot, 2010; Fuenfschilling and Truffer, 2014), the DT framework focuses on rules as a central coordination mechanism.

Rules are defined as humanly devised constraints and enablers that structure human action (adopted from North, 1990; see also Giddens 1984; Sewell 1992). In various domains of social life rules function as heuristics providing practical maxims to guide action, creating a sense of shared direction and coordinating human activity. Rules come in a variety of forms - informal or formal, unsanctioned or sanctioned, yet all these forms will leave traces that can be identified in some way or another. Some rules can be observed directly when used by actors in their speech and writings, whereas some are more tacit and hence need to be inferred from actors' regular patterns of action. Furthermore, the visibility of particular rules can change considerably over time: for example, when rules become broadly accepted, they shift into the taken-for-granted social repertoire of actors, and as such are often no longer verbalized by the actors.

In the DT framework socio-technical systems in a particular location at a particular time are seen as expressions of underlying rules (Schot and Kanger, 2018: 1053). This provides a strategy for going beyond numerous empirically observable and location-specific differences between socio-technical systems, and enables to identify deeper similarities in their basic logic of operation. To take a specific example: electricity might be generated from coal in China, nuclear in France and oil shale in Estonia. However, all these power plants are based on two principles that have characterized energy systems for more than a century: 'use fossil fuels' and 'centralize energy production'. From the DT perspective radical shifts within and between systems can therefore be traced through the emergence, diffusion and alignment of rules, providing multiple socio-technical systems with long-lasting directionality and shaping the behaviour of the actors that are part of the system.

The DT framework classifies rules according to whether one is dealing with a single rule or a set of rules aligned to each other, and whether the rule is present in one or multiple systems. This gives rise to a four-fold distinction between rules (single rule in one system), meta-rules (single rule in multiple systems), regimes (a rule-set in one system) and meta-regime (a rule-set in multiple systems). Table 1 provides an overview of these concepts.

[1] We use the term 'Transatlantic' as a shorthand for industrialized countries in North America and Europe, constituting a common space characterized by multi-directional flows of technological expertise, infrastructures, regulations, organizations and people. This formulation draws on prior historical literature (see Rodgers, 1998; Kaiser and Schot, 2014).

Table 1
Typology of rules.

Concept	Definition	Example
Rule	A humanly devised constraint and enabler that structures human action leading to a regular pattern of practice, present in a single socio-technical system	'Design cars for a nuclear family' as a rule in the mobility system
Meta-rule	A single rule present in multiple socio-technical systems	'Use fossil fuels as a source of energy for mechanized vehicles' in mobility (cars), food (tractors) and defence systems (tanks, airplanes)
Regime	Relatively stable and aligned rule-sets directing the behaviour of actors along the trajectory of incremental innovation, present in a single socio-technical system	'Produce standardized mechanized vehicles', 'Plan cars for obsolescence', 'Design cars for private use' and other interlinked rules as part of a new land-based road transport regime introduced in the first half of the 20th century
Meta-regime	Rule-sets present in multiple socio-technical systems, coordinating their development and leading to a shared directionality	'Use standardized parts in production', 'Organize a corporation as vertically integrated and multi-divisional', 'Buy a new product instead of repairing it' and other interlinked rules underpinning mass production, distribution and consumption in a broad array of systems and countries, especially after World War II

Source: Adapted from Kanger and Schot (2019: 9).

Using this analytical vocabulary, Schot and Kanger (2018) developed a model connecting transitions in single systems to five 'great surges of development' of 40–60 years each (Perez, 2010).[2] Building on the conceptual distinctions made by Perez (2002), the model relates the emergence, consolidation and maturation of rules to the phases of each surge. The exploration of this relation is the focus of our study. It is worth noting, however, that this model constitutes only a part of the broader set of propositions of the Deep Transitions framework (see Kanger and Schot, 2019: 13, for a full summary). Description of the phases of a surge and their relation to the dynamics of rules follows.

Gestation characterizes the protracted period before the beginning of the surge. New technologies and associated rules emerge in protected spaces called niches, characterized by specific demands on technological performance in particular applications, e.g. early steam engines being used to pump water out of mines. Occasional exogenous 'landscape' events might create pressures on dominant systems, providing a 'window of opportunity' for niches. The alignment of niche rules into new regimes would then lead to transitions in individual socio-technical systems (Geels, 2005).

The surge begins with the **installation** period that can be further divided into *irruption* and *frenzy* phases. Installation constitutes the first half of the surge, lasting about 20–30 years. During the *irruption phase* nascent niche rules and ones characterizing incumbent systems start to compete with each other. This can lead to transitions in single systems (or transition failures). Early multi-system interactions (e.g. between mobility and food) might also lead to rules crossing system boundaries, whereby the latter become meta-rules. However, in the irruption phase this movement remains rather random and does not generally lead to the establishment of lasting linkages. A clear directionality in multi-regime co-evolution is therefore yet to appear. Towards the end of *irruption* and beginning of the *frenzy phase*, however, the emergence of meta-rules intensifies. These dynamics generate both public enthusiasm about new technological opportunities as well as fears about their possible societal impacts. There is also some alignment between meta-rules, leading to a clearer direction of evolution. However, some alternative rules and meta-rules continue to exist.

The eventual alignment of meta-rules into a dominant meta-regime occurs at the **turning point**. Sudden crises such as World Wars provide powerful actors an opportunity to consolidate a certain rule-set and to close off alternative directions. From this point onwards, *the* dominant meta-regime has emerged, guiding the evolution of multiple socio-technical systems.

The **deployment** period, which can be divided into *synergy* and *maturity* phases, constitutes the second half of the surge (20–30 years in duration). The *synergy* phase is characterized by three developments: selection of niches compatible with the now-dominant meta-regime, the continuing diffusion and adaptation of the meta-regime in new systems, and the impacts of the meta-regime on the broader landscape. The gradual accumulation of problems generated by the meta-regime reaches a critical point in the *maturity* phase. Various societal and environmental issues prompt another surge, reflected in the emergence and scale-up of new rules in new niches. However, the previous surge has now become part of the landscape itself, expressed in established infrastructures, or environmental impacts. That is, the surge has added another layer to the socio-technical landscape that will structure new surges.

As a synthesis of sustainability transitions and long wave literature, the model presented above goes beyond both approaches in three ways. First, it connects niche- and regime-level processes to the dynamics of meta-regimes coordinating multiple systems. Second, the model explicitly incorporates the dynamics of rules during the long gestation phase. Finally, the co-evolutionary approach of the DT framework also suggests that mature meta-regimes continue to evolve after a new surge has begun. Perez (2002: 154) has referred to this process as 'rationalization', during which markets at the periphery are developed and production spreads to new locations. In contrast, the DT framework allows for the possibility that mature meta-regimes may respond to crises and opportunities associated with a new surge in ways that go beyond the mere optimization of existing practices. The DT framework thus entails a more extended observation period, covering the co-evolutionary dynamics of rules before and after the focal surge.

3. Research design

We use a single longitudinal case study design (Yin, 2018), selecting a 'most-likely' case (George and Bennett, 2005: 120–122). A most-likely case is expected to provide a close match with the theoretical propositions. Whereas most-likely cases do not provide a strong confirmation of a theory, a failure to find confirming evidence for a most-likely case seriously undermines the validity of the framework. This makes most-likely cases a good choice for first empirical tests of an emerging theory.[3]

Mass production, which we define as *the large-scale assembly of standardized parts into standardized goods aiming at capturing economies of scale*, was chosen for theoretical and empirical reasons. First, mass production can be conceived as a collection of mutually aligned rules, i.e. a meta-regime, with a substantial impact on many socio-technical systems such as mobility, food, defence or communications. Second, existing literature has identified mass production as a central element of the 4th great surge of development (Perez, 2002). A third consideration is about the availability of data for a mixed method approach, including

[2] 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).

[3] A similar (albeit implicit) reasoning was also followed in the early studies on single system case studies of transport, sanitation and production transitions (Geels, 2005; 2006a; Geels, 2006b). Less obvious cases such as rock'n'roll (Geels, 2007) were tackled only later after the initial approach had proven to be useful.

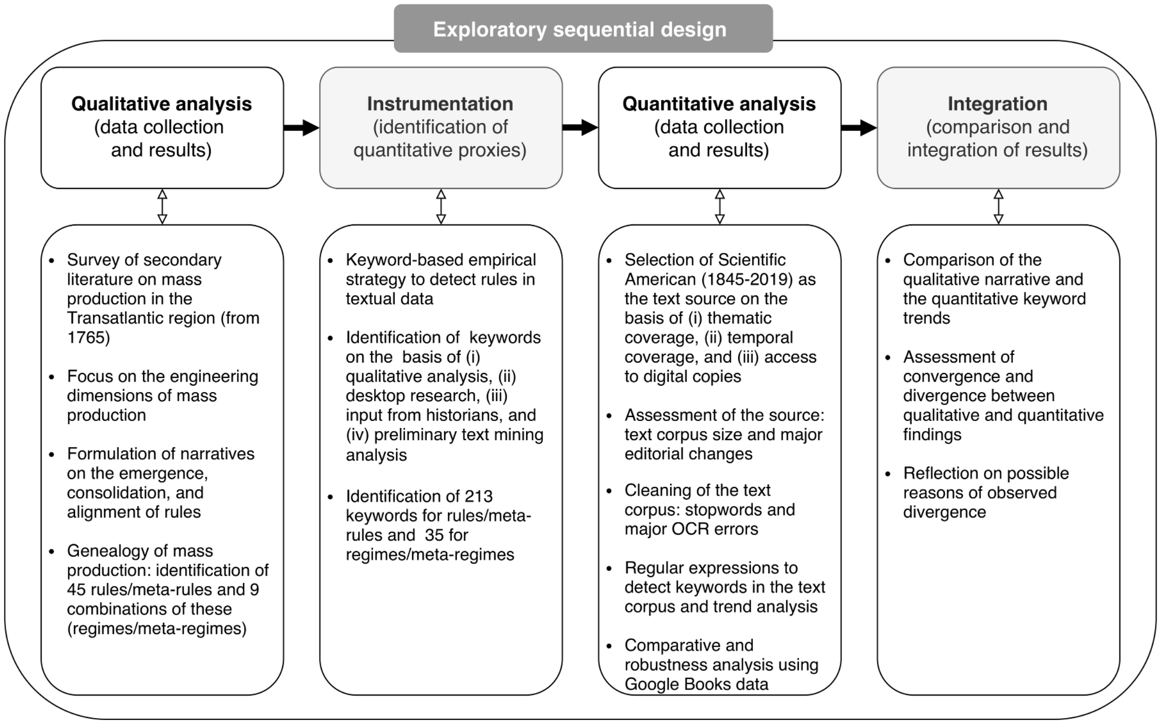

Fig. 1. Exploratory sequential research design as applied to the study of mass production. *Source: Authors' elaboration based on* (Creswell and Plano Clark, 2018; Creswell and Clark, 2018).

a suitable textual source (*Scientific American*) for a quantitative study and a wealth of secondary historical literature on mass production for qualitative examination.

Influential accounts in the study of both long waves (e.g., Freeman and Louçã, 2001; Perez, 2002) and transitions (e.g., Geels, 2005; Geels and Schot, 2010) have often relied on single or comparative case studies presented through stylized narrative explanations. This largely applies to existing works on multi-regime interaction as well (see Geels, 2007; Raven and Verbong, 2007, 2009; Sutherland et al., 2015; Hiteva and Watson, 2019). Whereas stylized narratives provide granularity in describing complex dynamics and multi-faceted topics (Geels, 2011), this strategy has also been criticized for subjective researcher choices, selective treatment of data and unclear standards for assessing whether the results conform to expected patterns or not (Genus and Coles, 2008; Sorrell, 2018). Furthermore, because of feasibility considerations, such studies are often assembled through a synthesis of secondary historical literature, thus leaving the researcher largely dependant on the availability of prior historical studies.

To address these limitations, we expand the qualitative historical analysis of mass production with a quantitative full text analysis. Advances in Natural Language Processing (NLP) techniques have recently enabled the application of text mining to the study of cultural trends (Michel et al., 2011; Lansdall-Welfare et al., 2017), historical development of ideas and institutions (Barron et al., 2018), long-term continuity and change in discourse (Klingenstein et al., 2014; Rule et al., 2015), technological emergence and evolution (Kapoor and Klueter, 2020; Kelly et al., 2020), industry convergence (Kim et al., 2015) and the identification of focal points in sustainable development strategies (Sebestyén et al., 2020). As discussed later in the paper, we selected a primary textual source that covers most of the observation period, and a second one to cross-check the results of the first source. This approach reduces the need for *ex ante* selection of the frequency and timing of specific topics in the textual source. It therefore provides an alternative and complementary way to assess the claims of qualitative stylized narratives.

We adopt an exploratory and sequential version of mixed methods research design. This design is particularly suitable for instances in which a researcher wants to test some aspects of an emerging theory, develop a quantitative instrument where none exists and assess the generalizability of qualitative results (Creswell and Clark, 2018: 86). The exploratory sequential design consists of four phases: (i) qualitative analysis, (ii) instrumentation, (iii) quantitative analysis, and (iv) integration. In the first phase, the researcher first collects and analyses qualitative data to obtain an in-depth understanding of the phenomenon, including an idea of what should be measured in the first place. The results are used to develop a quantitative approach through instrument design or variable identification. The following quantitative phase seeks to apply the instruments to a new sample, i.e. a sample other than the one from which the instruments were drawn. Finally, the researcher compares the results and integrates the findings (Creswell and Clark, 2018: 84–93). The different steps as applied to the study of mass production are illustrated in Fig. 1 and described in more detail below.

3.1. Qualitative analysis

The qualitative analysis was carried out in four stages. In the first stage the combination of influential works on the history of mass production (e.g. Hounshell, 1985; Tolliday, 1998; Nye, 2013) and literature searches (in databases such as Project MUSE, JSTOR, ScienceDirect), was used to create a preliminary list of secondary literature, further expanded through snowball sampling. For feasibility considerations the study was restricted to the engineering dimension of mass production, i.e. rules underlying the use of technologies and materials, organization of production and labour control. The economic, political, social and cultural components of the 4th surge (e.g. business strategies such as planned obsolescence, new corporate structures, state intervention in economic activities, ideology of consumerism) were excluded.

On the basis of the secondary literature, the various technologies and organizational practices were translated into rules through the process of creative interpretation, involving a constant shift between specific descriptions and analytical abstractions (see Appendix A for examples). This resulted in a genealogy of mass production (see Fig. 2) covering 45

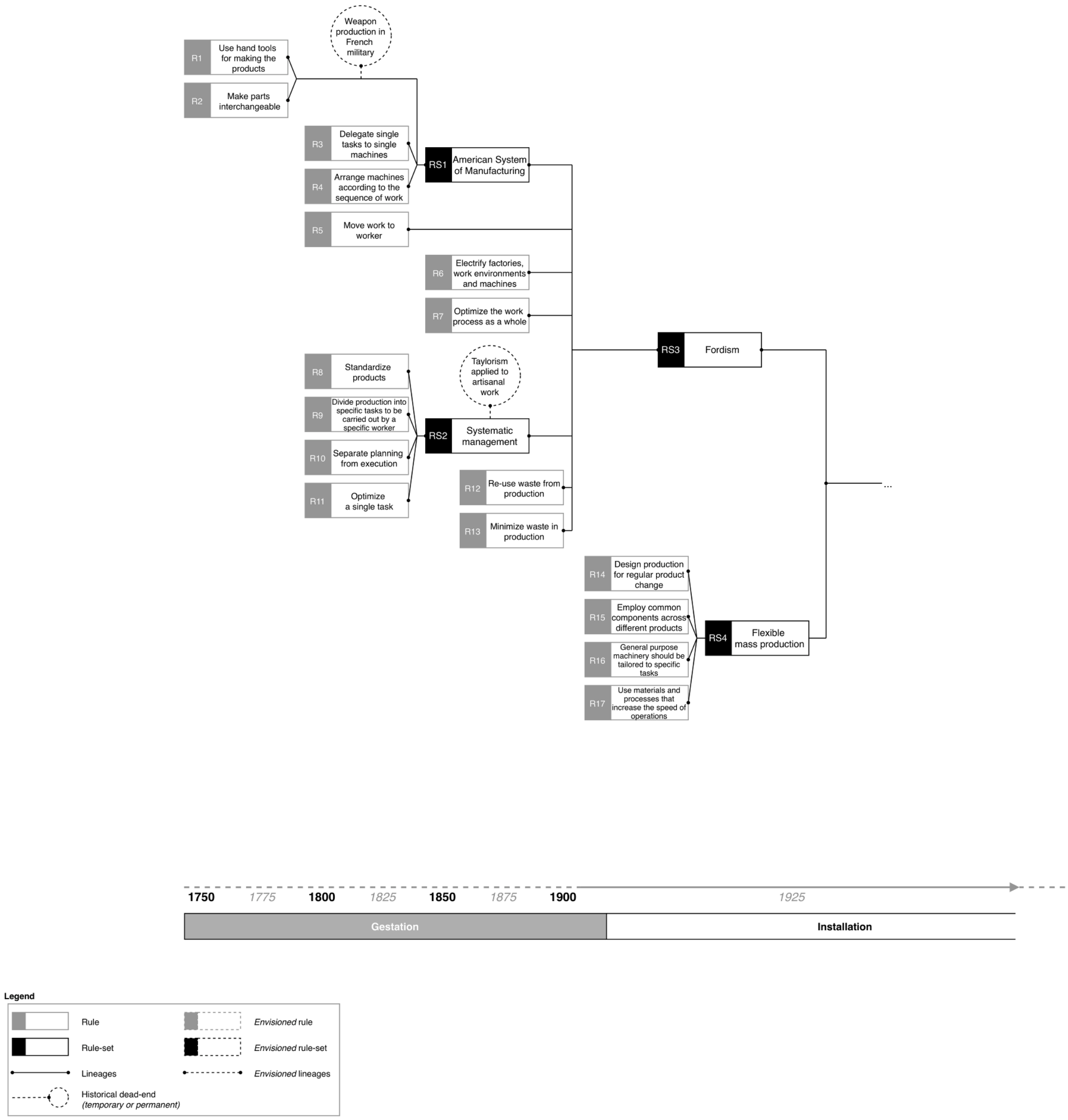

Fig. 2. The genealogy of single rules and rule-sets associated with mass production. *Source: Authors' elaboration based on Kanger and Sillak (2020).*

rules and meta-rules, and 9 combinations of these (regimes/meta-regimes). Although there is no strict analytical standard for determining the 'appropriate' level of aggregation for rules, the interpretive work aimed at a balance between feasibility and triviality. This was based on the assumption that an overly granular approach (with a high number of rules) would have created serious operationalization challenges, whereas an approach with a low number of highly generic rules (e.g. 'mechanize', 'digitalize') would not have generated very substantive results. In order to validate and improve the genealogy the results were discussed with two historians of technology, authors of influential works on mass and specialty production.

Based on the review of secondary literature and using the genealogy as a guide, a narrative explanation of the emergence, consolidation, maturation and crisis of the mass production meta-regime was then created. The narrative was discussed with research team members and external researchers in project workshops to detect possible inaccuracies, gaps and oversights. This was followed by additional work with historical literature to address the identified shortcomings.

The qualitative analysis was concluded by pattern-matching (Yin, 2018: 224–225), aiming to contrast theoretical propositions with empirical observations. Two researchers first conducted a separate interpretive assessment of the extent to which the findings were 'largely in line with' or 'sufficiently deviant from' the theoretical model, followed by a discussion to resolve outstanding differences. Where necessary, further conceptual extensions were developed to explain the findings. Detailed qualitative results and analysis, including the identification of additional empirical patterns not covered in this study, can be found in Kanger and Sillak (2020).

3.2. Instrumentation

Our aim was to identify an empirical strategy for tracing single rules and rule-sets in textual sources. For this purpose, we proxied rules with a set of keywords derived from the specification of rule, and determined the frequency of these keywords in the text corpus of the examined source. This approach assumes that the frequency and timing of keywords is a proxy of the emergence, stabilization, and alignment of rules. The specification of keywords for each element of the genealogy was

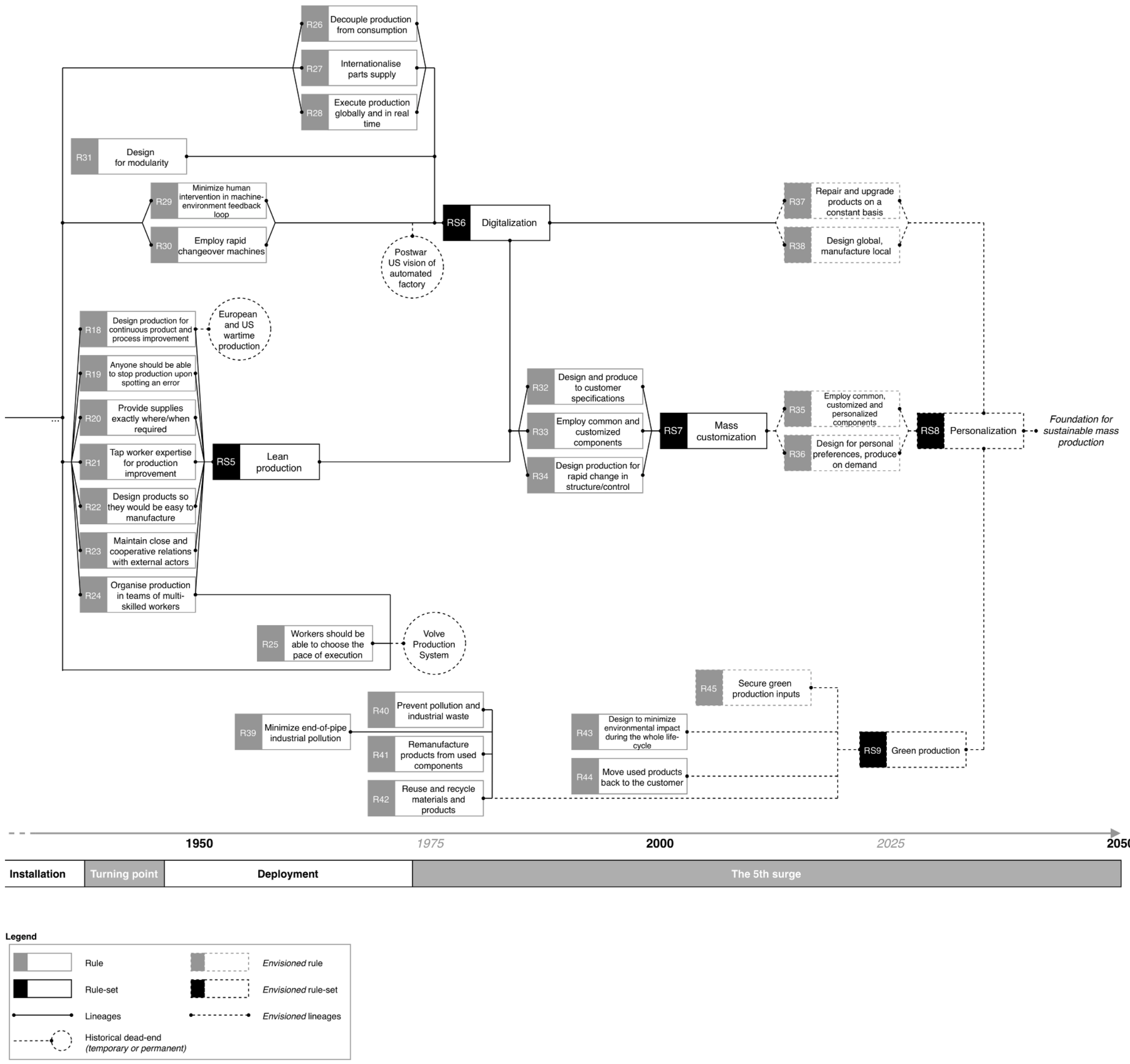

Fig. 2. (*continued*).

performed by the research team, based on the results of our qualitative analysis as described above, including advice from historians who were consulted in the development process. This enabled us to identify a total of 213 keywords for rules and 35 keywords for rule-sets – at least three keywords were identified for each rule (see Appendix B for full information).

Where possible, qualitative results from the first step were used to generate a set of tentative expectations for the findings of text mining analysis. These have been made explicit in our presentation of the results in Section 4 (see Table 2). However, since we did not have a detailed understanding of how exactly the theoretical propositions would manifest themselves in textual data, the instrumentation and quantitative phases were partly exploratory in nature.

3.3. Quantitative analysis

We consulted two expert historians, asking them to assess the suitability of different trade journals (e.g. *Automotive Industries, Automotive Service Digest, Automotive Topics*, and *Roads and Street*) and engineering magazines (e.g. *American Machinist, Engineering Magazine*, and *MIT Technological Review*). Based on this discussion we decided against using these sources because of their fairly narrow focus on specific sectors and audiences as well as limited availability of digitalized issues. *Scientific American* – a source devoted to the coverage of a broad range of topics on science and technology – was instead chosen for its suitability in studying the installation and deployment of the mass production meta-regime in various systems. While *Scientific American's focus on the US* limits the generalisability of our findings, it also provides rich contextual information for interpreting the emerging results of the text mining analysis since the evolution of the mass production in the US was pivotal to its global development and has been subject of extensive examination (see Hounshell, 1985; Tolliday, 1998; Nye, 2013). Having been published from 1845 without interruption, *Scientific American* offers continuous coverage for most of the observation period in a digital format. This is extremely rare for a magazine focussed on science and technology, hence, given the length of the observation period, *Scientific American* is a particularly suitable source for our study.

The journal has been subject to two major changes in editorship. These resulted in a significant shift of the focus of *Scientific American*: from 1846 to 1948, editors of the Munn family (1846–1948) focussed the magazine on topics related to inventions and manufacturing; from 1948, the new editors (Gerard Piel, Dennis Flanagan, Donald H. Miller) redirected the focus to science. For example, in the early years, *Scientific American* included a relatively large proportion of discussions around patents. These disappeared over time with the new editorship. As shown by Stefaner et al. (2020), this shift led to some changes in the vocabulary of *Scientific American* – a first shift around 1870 marking the change in the presentation of new inventions (earlier detailed discussion of new

Table 2
Propositions of the DT framework and expected results.

Theoretical proposition	Expected results for the case of mass production *Qualitative evidence*	*Quantitative evidence*
GESTATION (before the 4th surge)		
Before the surge, rules emerge and compete in several niches of individual socio-technical systems without much coordination	Evidence of the precursors of mass production and partial combinations of these rules originating from different areas of application	Increasing occurrences of the keywords associated with R1-R13 and RS1 and RS2 but with no particular pattern in timing and emergence
INSTALLATION (4th surge)		
Irruption: emerging and incumbent rules and regimes come to compete against each other in individual systems, resulting in transitions	Competition between various production-related rules, formation of the mass production regime	Increasing frequency of keywords associated with various single rules related to mass production (R1-R13)
Frenzy: rules increasingly cross the boundaries of single systems and partially align to each other, leading to the formation of alternative, possibly competing rule-sets	Attempts to further develop the mass production regime, competition between mass production and its variations	Emergence and increasing frequency of terms denoting the mass production, especially from the frenzy phase, reflecting the increasing public visibility and different variations of large-scale production (RS2–4) Emergence of keywords denoting rules associated with the further evolution of mass production (R14-R17)
TURNING POINT (4th surge)		
Tipping of the scales decisively in favour of one meta-regime that becomes dominant	Various effects of World War II: mass production gains an increasing foothold in several systems and expands to new areas of application	Increase in both keywords denoting rules part of mass production (R1-R17) as well as terms denoting mass production itself (RS3)
DEPLOYMENT (4th surge)		
Synergy: the dominant meta-regime selects niches compatible with its logic, diffuses to various systems and starts to shape the landscape	'Golden age' of mass production, including its optimization and its expansion into new systems and countries	Continued prominence of keywords denoting the dominant meta-regime of mass production (R1-R17, RS3 and RS4)
Maturity: the dominant meta-regime loses its grip and the cycle re-starts with other niches, systems and rules becoming central to the new surge	Emergence of new rules and partial combinations of these rules, challenging the dominant version of mass production	Gradual emergence of keywords associated with various alternatives to the dominant version of mass production (R18-R30, RS5 and RS6)
INSTALLATION (5th surge)		
The framework makes no propositions about the behaviour of mature surges during the emergence of the next one	–	–

Note: The numbering of rules and rule-sets is based on Fig. 2. *Source: Authors' elaboration.*

patents vs. brief summaries later on) and a second one marking the topical coverage towards science.

As such changes are likely to affect any text source over such a long period of observation, we used a second text source to compare our results and to ensure that the observed trends would not be specific to our primary source. Since there are very few data sources that cover socio-technical dynamics with similar temporal breadth, we eventually decided to focus on *Google Books*, which aggregates millions of digitized sources targeting a variety of audiences and themes (Michel et al., 2011; Pettit, 2016). While *Google Books* is a good fit for validating the results, it suffers from two important limitations which would make it unsuitable as the primary source for text analysis. First, it is challenging to build a qualitative understanding of the evolution of *Google Books* due to a lack of metadata relating to how the composition of its text corpus has evolved (Pechenick et al., 2015; Koplenig, 2017). In the case of *Scientific American*, access to the full text of issues and articles and the availability of studies examining the evolution of *Scientific American* (e.g. Oreskes and Conway, 2020; Stefaner et al., 2020) enabled us to develop a qualitative understanding of this source and its corpus – such as changes of format, editors, and target audience as outlined above – to make informed interpretations of the findings, and to identify limitations and caveats in our analysis. Second, while the meaning of a keyword is unlikely to remain stable in any historical textual sources spanning over a century, this issue is likely to be more prominent in *Google Books* than *Scientific American*: the former is an evolving aggregation of a large variety of sources addressed at many audiences (Pettit, 2016), while with the latter, changes in nature of the source and its audience can be more clearly delineated. For example, the keyword "tolerance" may with some confidence be interpreted as a technical term in the *Scientific American* while this is less so for *Google Books.* For these reasons we decided against *Google Books* as a main data source, but did use it for cross-checking our text mining results from *Scientific American* (see below, and Appendices B and C).

Historical patent data constitute another possible source to study the long-term dynamics of socio-technical systems. An emerging stream of work, mostly focused on US patents, has relied on historical patents to examine the geographical location of inventions (Petralia et al., 2016), to develop economic indicators of innovation (Kogan et al., 2017), and to trace breakthrough inventions and technological evolution over long periods (Kelly et al., 2020). Yet, in our study, we aim to capture the evolutionary dynamics of regular patterns of practice, i.e. rules and rule-sets, which may be too generic to be patentable or observed in documents that are mostly focused on describing inventions from technical and legal perspectives. As patents primarily represent a mechanism of intellectual property protection for novelty, they are less likely to provide evidence of the sustained public prominence of rules and rule-sets than journals.

We built the text corpus of *Scientific American* from August 1845 to June 2019. The data source includes 5,065 distinct issues, which we collected in PDF files from Nature's website. JSTOR and ProQuest databases were also queried to fill any missing issues.[4] Each issue was processed using Optical Character Recognition (OCR) to extract its full text. We then searched for all the keywords representing rules and rule-sets in the corpus of *Scientific American* using regular expressions to capture variations in the spelling of keywords. As the frequencies of keywords can vary considerably between consecutive years, the results presented in the next section are reported using a 5-year moving time window, i.e. the occurrence of a keyword at time t is derived from the cumulative sum of frequencies of the keyword in years $t-2, t-1, t, t+1$ and $t+2$. Results are qualitatively the same with wider moving time windows. Also, the frequencies of keywords are reported in terms of percentage of the cumulative size of the text corpus in the corresponding time window. This is to account for the changing size of text corpus over the observation period due to major changes to the magazine format: in 1846, *Scientific American* changed the length of the issues from four to eight pages; in 1859, issues were further expanded to 16 pages; in 1921, the number of issues per year was reduced from 52 to 12 issues; and in 1948, a major editorship change led to a significant growth of the text

[4] The coverage gap is of only 6 issues (0.01%). These issues were not available from any of the databases we queried.

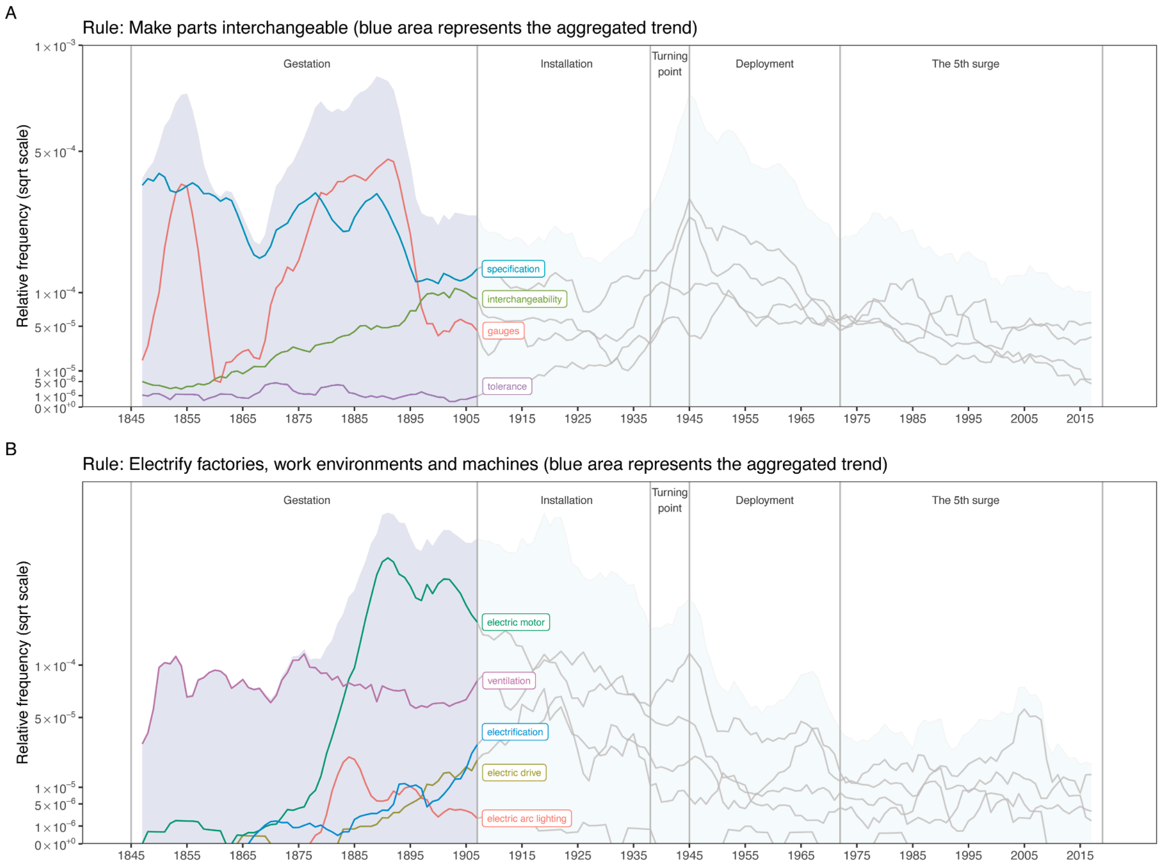

Fig. 3. Frequency of keywords associated with rules [R2] 'make parts interchangeable' (A), and [R6] 'electrify factories, work environments and machines' (B) in *Scientific American* during the gestation of mass production. *Source: Authors' elaboration.*

length of issues.

The text mining analysis of the corpus of *Scientific American* detected about 59% (or 126/213) of the keywords associated with rules and 49% (or 17/35) of the keywords associated with rule sets. For clarity, we present the time series with a sufficient level of occurrences to form a trend, i.e. keywords that occurred at least 97 times or in 0.0001% of the processed corpus. This led us to focus on a total of 28 keywords for rules and 6 keywords for rule sets. It should be emphasized that in the next sections we focus on the most informative results, while the complete keywords frequencies are reported in Appendix B.

Having completed the work on the *Scientific American* corpus, we also ran a robustness analysis comparing trends between *Scientific American* and *Google Books* to assess potential idiosyncrasies of the keyword trends observed in *Scientific American*. However, since this analysis did not provide evidence of major misalignments between the two sources, we therefore decided to present the results in Appendix C, while focusing on main results found in the *Scientific American* in the body of the text.

3.4. Integration

In the final stage qualitative and quantitative results were summarized and contrasted with each other to obtain an overview of similarities and differences between the findings. The possible reasons behind observed differences were discussed with the team. Substantively, the quantitative assessment provided an alternative way to check the qualitative claims about the presence, timing and magnitude of certain rules and rule-sets. Methodologically, the integration stage also led to an increased understanding of the opportunities and limitations of using keywords as a proxy for the co-evolution of rules (see Section 5).

4. Results

This section presents a narrative description of the overall dynamics of rules, meta-rules, regimes and meta-regimes along with quantitative evidence from text mining, covering the following phases:

(i) gestation (1765–1907);
(ii) installation of the 4th surge (1908–1938) ,[5] including irruption (1908–1919) and frenzy (1920–1938);
(iii) turning point (1939–1945);
(iv) deployment of the 4th surge (1946–1972), including synergy (1946–1959) and maturity (1960–1972);
(v) evolution of mass production during the 5th surge, centred on Information and Communication Technologies (from 1973).

Fig. 2 presents the approximate rule-based genealogy of mass production during the entire observation period as derived from the qualitative analysis (i.e. including all of 45 rules and 9 rule-sets). Table 2 presents each theoretical proposition along with tentative expectations for qualitative and quantitative evidence.

4.1. Gestation (1765–1907)

The antecedents of mass production can be traced back to 1765 when the idea to make weapons from interchangeable parts was conceived in the French military (Hounshell, 1985). The feasibility of this principle was first demonstrated with hand tools: however, the pursuit towards interchangeability in French arms-making was eventually terminated

[5] This largely follows the periodization by Perez (2002).

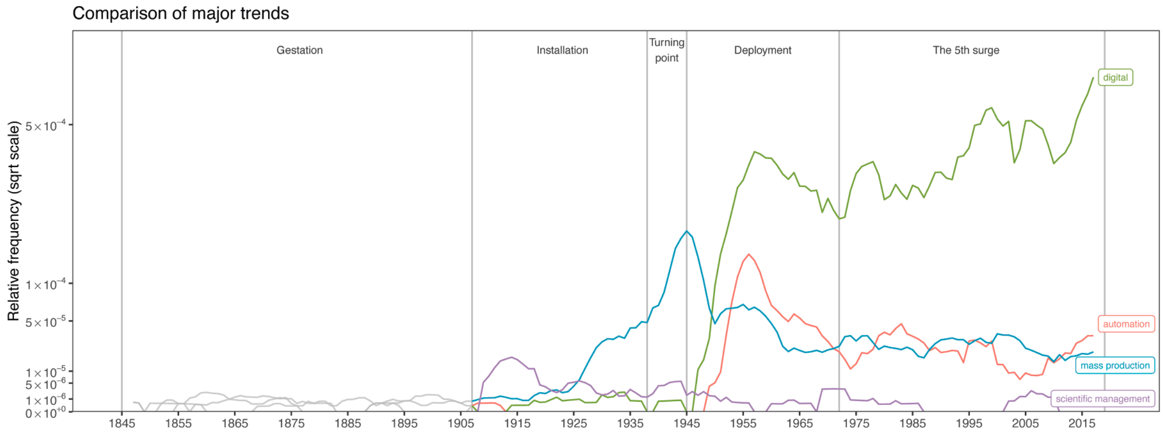

Fig. 4. Comparison of major trends on ‘scientific management’, ‘mass production’, ‘automation’, and ‘digital’ from the installation period to the 5th surge in *Scientific American*. Source: Authors’ elaboration.

for political reasons (Alder, 1997). A further technical advancement was made in American armouries during the first half of the 19th century when the principle of interchangeability was combined with the use of special-purpose machinery and sequencing of machines according to the process of work. The alignment of these three rules constituted the core of the ‘American System’ (Smith, 1977; Hounshell, 1985). In addition to the standardization of parts, product standardization also gained strength as a new rule, potentially enabling the avoidance of expensive and time-consuming retooling (Nye, 2013). Fig. 3A shows that some concepts associated with the rule ‘make parts interchangeable’ appear in *Scientific American* from the very first years (1845–1855) in which the journal was published.

Qualitative evidence largely confirms the expectation about the emergence of rules in various niches over the 19th century. For example, ‘move work to worker’ rule was experimented with in meat-processing, Edison’s iron mining facility and bicycle production (Hounshell, 1985; Beniger, 1986; Nye, 2013). Electrification constituted another important trend, with the introduction of electric motors in the 1880s and a gradual move toward unit drive installations over the next decades. Electrified lighting and ventilation also enabled increases in working time, improved precision and better health outcomes for the workers (Geels, 2006b). The quantitative analysis provides evidence of the emergence of a number of terms related to the rule ‘electrify factories, work environments and machines’ (see Fig. 3B). These include terms such as ‘ventilation’, ‘electric motor’, ‘electric arc lighting’, ‘electrification’, and ‘electric drive’. For example, the term ‘ventilation’ occurred with relatively high frequency since 1845, but its use increases and then stabilizes later on. The use of terms like ‘electric motors’, ‘electrification’ and ‘electric drive’ also intensifies, but a few years after ‘ventilation’. These findings suggest that the vocabulary around electrification has developed to a great extent in the gestation phase, likely reflecting various applications of electricity.

Starting from the last quarter of the 19th century, proponents of the Efficiency Movement focused on the minute division of production into specific tasks, optimization of both work tasks and the overall work process, separation of work planning from execution, and minimizing or re-using production waste (Beniger, 1986; Biggs, 1995; Geels, 2006b). These principles were occasionally combined, e.g. Frederick Winslow Taylor’s gradually emerging ‘scientific management’. However, evidence of these management-related trends in *Scientific American* remains scant. Apart from this, we find that the combination of qualitative and quantitative results largely confirms the theoretical proposition, i.e. pre-surge emergence and circulation of rules without much coordination.

4.2. Installation of the 4th surge (1908–1938)

The period between 1908 and 1915 – especially the last three years in the Highland Park factory – was characterized by a wave of experimentation by Henry Ford and his team of engineers (Hounshell, 1985). Although many production principles had already been known in the 19th century (see Section 4.1), it was the alignment of these principles into a new mass production regime that constituted a real breakthrough in the mobility system. In comparison to a contemporary alternative - Frederick Winslow Taylor’s “scientific management” - Ford focused on the optimization of the entire work process (vs. the optimization of single tasks. In terms of productivity this approach turned out to be a huge success: already in 1914 Ford’s assembly line produced 30 times as many cars per worker as the ‘Taylorist’ Packard factory (Nye, 2013: 250). By 1920, half of the automobiles in the world were Ford Model T-s (McShane, 1997: 57). The outcomes of this competition are well reflected in Fig. 4 which shows that the initial popularity of ‘scientific management’ was superseded by ‘mass production’ by the mid-1920s, interpreted as the expected pattern of alignment.

World War I accelerated attempts to extend mass production from the mobility system to defence and food systems, e.g. the French company Citroën starting to produce artillery shells or Ford introducing the Fordson tractor in 1917. From the 1920s the prevalence of mass production in these systems was reflected in trends such as the take-up of automobiles (primarily in the US), anticipation that future wars will be increasingly mechanized, and the continued mechanization of agriculture. Mass production was often introduced to new systems through various consumer durables, e.g. communication (radio sets) and housing (washing machines, vacuum cleaners, electric irons) (Nye, 2013: 51). This process was also marred with several setbacks, e.g. too optimistic expectations that mass production can be readily extended from cars to submarine patrol boats (Ford during WWI), or failed experiments to produce prefabricated houses on the assembly line (USA and Europe, interwar era) (Hounshell, 1985).

Although Ford had a first-mover advantage, reaping massive profits from the production of the Model T, the need to stay competitive prompted General Motors to look for new ways for combining product diversity with economies of scale from the 1920s. Through the introduction of rules such as designing production for regular product change, employing common components across different car models or customizing general-purpose machinery for specific tasks, ‘flexible mass production’ was thus created (Hounshell, 1985). Another direction of activities concerned the use of materials and processes for increasing the speed of operations. In Europe, attempts to borrow selectively from Ford, Taylor and General Motors often resulted in localized innovations such as the Fayolism and Bedaux systems in France or Bataism in

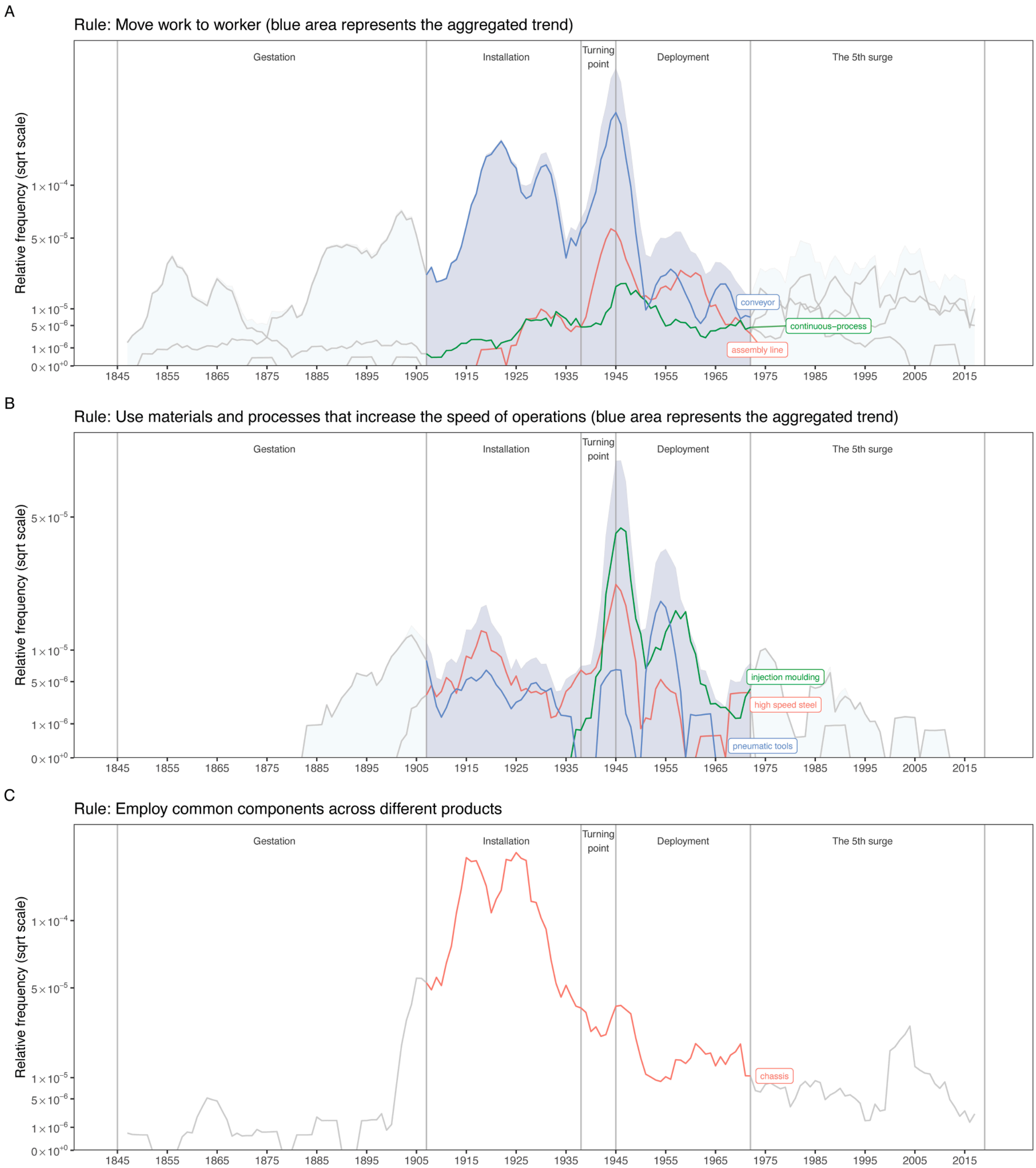

Fig. 5. Frequency of keywords associated with rules [R5] 'move work to workers' (A), [R17] 'use materials and processes to increase the speed of operations' (B), and [R15] 'employ common components across products' (C) in *Scientific American* from the installation to the deployment period. Source: Authors' elaboration.

Czechoslovakia (Schröter, 2007; Kohlrausch and Trischler, 2014: 125–139).

The presence of various rules relating to mass production can also be detected in *Scientific American*. The 'move work to worker' rule becomes highly visible during the installation period as evidenced by the increasing frequency of terms such as 'assembly line', 'continuous-process', and 'conveyor' (see Fig. 5A). The same is true for the 'use materials and processes to increase the speed of operations' rule, exemplified by the increasing frequency of terms such as 'injection moulding' and 'high speed steel' (see Fig. 5B). In the same vein, the rule 'employ common components across products' as represented by the keyword 'chassis' is particularly prominent during the installation phase (see Fig. 5C). It is, however, worth noting that these terms are also frequently used in the post war period after 1945. This suggests that certain rules can become salient in different phases of the surge (and possibly even during successive surges).

In contrast to rules associated with 'Fordism' *Scientific American* does not provide clear evidence of 'flexible mass production'. This might be partly related to the fact that General Motors is better known for business and management innovations, including multi-divisional decentralized management structure, consumer credit, and the trade-in of used cars. As our study focused on the engineering dimension, and the focus of the source is primarily on technical developments, General Motors's business innovations would not show up in our analysis.

The qualitative research thus largely confirmed the proposition that during the installation phase rules and meta-rules compete against each other (e.g. competition between mass production and scientific management) leading to a transition in one system (mobility) and then gradually extending to other ones (e.g. defence, food, followed by communication and housing). Text mining provided some evidence of competing rule-sets and also confirmed the growing importance of rules related to mass production. However, quantitative evidence remains scarce on rules related to 'flexible mass production'.

4.3. Turning point of the 4th surge (1939–1945)

Wartime requirements dramatically created demand for standardized products in all countries participating in the conflict. Mass production of cars, tanks, airplanes, ships, food, uniforms, tractors etc. was considerably accelerated through government procurement or other subsidies such as investments in new factory equipment (Gordon, 2016). Additional stimulus was provided by the need to share supplies to allies, e.g. the Lend Lease act of 1941 (Nye, 2013). Indirect factors included the forced savings of a large number of soldiers (Gordon, 2016) and the devastation of war, raising pressing concerns about the need for increased output. The combined impact of all these factors was the build-up of mass production capacity that could be converted for civilian purposes after the war.

These developments are also partly reflected in *Scientific American*. For example, in the case of the 'move work to worker' rule terms such as 'assembly line', 'continuous-process' and 'conveyor' peak during war time (see Fig. 5A). Similarly, the relative frequency of terms as 'injection moulding' and 'high speed steel' peaks in the turning point period, thus providing evidence of a consolidation of the rule 'use materials and processes to increase the speed of operations' (see Fig. 5B). Furthermore, rules that emerged in the gestation period – i.e. 'make parts interchangeable" and 'electrify factories, work environments and machines' – resurged during the war (see Fig. 3). The use of the general term 'mass production' peaks in the same period as well (see Fig. 4). Taken together, these findings provide evidence of the increased significance of mass production and appear to confirm the qualitative research results.

On the other hand, historical literature also stresses that wartime conditions meant a special emphasis on complex product performance. For example, Zeitlin (1995) has described how Americans, British and Germans sought different ways to manage the trade-off between the quantity and quality of airplanes. This, in turn, led to experiments with continuous improvement of production and just-in-time supply provision. However, as the strong need for continuous improvements in complex product production disappeared with the end of WWII, these nascent principles were largely abandoned by the Transatlantic countries. This might explain why these experiments have been discussed in secondary literature but do not show up in *Scientific American*.

4.4. Deployment of the 4th surge (1946–1972)

The aftermath of WWII was characterized by the consolidation of the mass production meta-regime along several dimensions. This included the know-how and infrastructure for standardized production (science/technology), horizontally integrated and multi-divisional large corporations (economy), social contract between employers, labour and policy-makers within the framework of a nationally-bounded welfare state (policy), individualized private mass consumption (everyday life), and the ideology of social progress (culture) (Freeman and Louçã, 2001; Perez, 2002; Trentmann, 2016). Mass production was increasingly present in a number of systems, e.g. rapid diffusion of private vehicles and growing road infrastructure in the mobility system, diffusion of fast food chains and the breeding of animals and plants to make them compatible with industrial agriculture in the food system, or the standardized approach to building construction in the housing system (Nye, 2013). American-style principles of production, distribution and consumption entered Western European countries to such an extent that the process was often described as 'Americanization', albeit with important regional differences (Zeitlin and Herrigel, 2000; Schröter, 2007).

Whereas the qualitative analysis confirms the adoption of mass production in new systems and locations, our quantitative analysis finds the frequency of keywords signifying mass production and its constituent rules gradually decreasing from WWII (see Figs. 3–5). In other words, increasing diffusion of mass production was paralleled by the decreasing discussion of this process. We will return to the significance of this finding in Section 5.

Attempts to further develop mass production proceeded in two directions. Beginning from the 1950s, labour unrest in American factories stimulated future visions of fully automated factories, combining the principles of minimizing human intervention in machine-environment feedback loop (e.g., computer-aided design and manufacturing) with the employment of rapid changeover machines. Correspondingly, in *Scientific American* terms such as 'automation' and 'digital' rapidly peaked in this period, reaching levels of usage comparable to 'mass production' (see Fig. 4). However, while the frequency of automation declines in the deployment period, 'digital' continues on an upward trend both in the deployment period and the 5th surge. A qualitative analysis highlights the 'automation' hype of the 1950s as a likely reason. In these years, influential experts such as Norbert Wiener and John Diebold believed full automation would be realized by the beginning of the 1960s. However, technical difficulties considerably delayed actual implementation, and the number of robots in American factories remained modest (Nye, 2013: 157–161). Qualitative and quantitative analyses thus yield similar results, corroborating our initial expectations that new alternative rules would emerge although they would not necessarily be widely adopted at the time.

Another instance of contesting the dominant meta-regime is provided by Toyota who, beginning from the late 1940s, began adapting American-style mass production to Japanese conditions: smaller market, greater variety of models and lack of capital for investment in machinery. Prioritizing the minimization of errors rather than speeding up throughput, the Japanese gradually institutionalized many ideas, e.g. designing production for continuous improvement, allowing workers to stop the assembly line to correct errors, just-in-time supply, tapping worker expertise for production improvement, product design aiming to make manufacturing as easy as possible, maintaining tight collaborative relations with supply chain partners and organizing production in teams of multi-skilled workers (Nye, 2013). These rules were gradually refined and formally documented for the first time in the mid-1960s as the Toyota Production System (Holweg, 2007). At the time, however, little was known about these advances outside Japan. Possibly for these reasons *Scientific American* contains little evidence of Toyota's experiments during the deployment period. For example, terms associated with the rule 'design production for continuous product and process improvement' (i.e. 'continuous improvement', 'fine tuning', 'process refinement' and 'kaizen') occur very rarely or do not follow any meaningful pattern (see Appendix B for more detail).

The Border Industrialization Program of 1965 encouraged some US enterprises to outsource some manufacturing activities to northern Mexico (Ericson, 1970). This signals an expected maturation of the meta-regime, i.e. attempts to maintain profitability by further optimization of labour costs. This also meant the introduction of international parts supply and a geographical separation between manufacturers and end users that were to become the defining features of mass production in the 1970s. However, quantitative analysis offers little evidence of these processes being discussed in *Scientific American*. This may reflect the gradual change of *Scientific American* from a technology-orientated source to a science magazine after the 1950s.

4.5. The 5th surge (1973-…)

By the end of the 1960s various problems with mass production had become apparent: it was frequently accused of being rigid, inflexible, reliant on large buffer stocks and a source of low labour motivation. In terms of its broader societal impact, it was criticized for promoting cultural homogenization and over-consumption as well as for its increasingly apparent contribution to environmental pollution and resource depletion (Nye, 2013). This prompted various attempts to

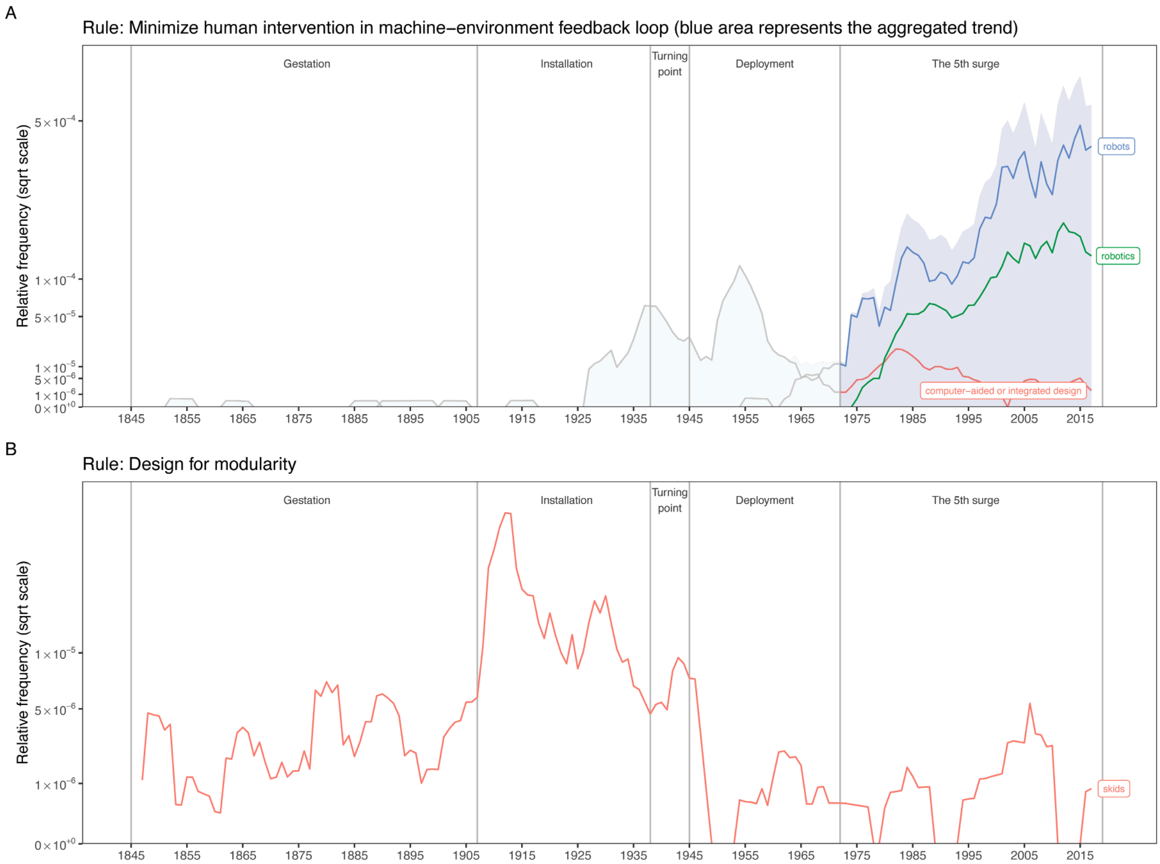

Fig. 6. Frequency of keywords associated with rules [R29] 'minimize human intervention in machine-environment feedback loop' (A), [R39] 'minimize end-of-pipe industrial pollution' (B), and [R42] 'reuse and recycle materials and products' (C) in *Scientific American* from the deployment period to the 5th surge. *Source: Authors' elaboration.*

resolve these issues either through further optimization or more encompassing transformation.

From the 1970s, the decreasing profitability problem was often addressed by the further expansion and deepening of neofordism which we interpret as the optimization of American-style mass production. Making increasing use of information technologies, mass production was gradually connected to the principles of global organization and real-time coordination of production. Despite the broad impacts of neofordism, including a significant shift of manufacturing activities from developed to developing countries and the emergence of a new industrial division of labour (Fröbel et al., 1980; Milanovic, 2016), evidence of these developments could not be detected in *Scientific American*.

Beyond optimization, internal transformation of mass production was attempted along three dimensions: reorganization of work, digitalization and greening. The prime example of the former is the Japanese 'lean production' (Krafcik, 1988) that, beginning from the 1980s, was increasingly adopted by American and European factories including factories constructed by Japanese companies. Relying on the combination of rules pioneered over previous decades (see Section 4.4), its impact on product quality, productivity and efficiency was such that it has been interpreted as a qualitative leap in the evolution of mass production (Nye, 2013). Also notable were Volvo's attempts to address labour motivation issues, e.g. by stopping the assembly line and letting the workers choose their own pace of work (Muffatto, 1999). However, quantitative evidence of these rules and rule-sets in *Scientific American* continues to be scant. Possible reasons for this include the journal's primary focus on American topics and, from the 1960s, increasingly on science.

The second stream was related to increasing digitalization of production. After the initial 'automation' hype of the 1950s and a dip in the 1960s, digitalization-related keywords started to increase in frequency from the 1970s. This applies to specific rules part of the digitalization rule-set as well as the overarching term itself. For example, Fig. 6A shows a rise in keywords like 'robotics' or 'computer-aided design' whereas Fig. 5 shows growth in the word 'digital'. From the 1980s ideas about modular design, setting up production for rapid changes in structure and control, employment of common and customized components or design and production to customer specifications were all implicated in the 'mass customization' vision (Fogliatto et al., 2012). An even more recent trend of 'personalization' stresses the use of personalized components and on-demand production (Hu, 2013). However, these rules and rule-sets are virtually absent from the text corpus. This also applies to recent attempts to connect peer production and manufacturing, e.g. constant repair/upgrade and 'design global, produce local' principles (Kostakis et al., 2015).

From the 1970s increasing environmental concerns led to the introduction of new production principles, first centred on the end-of-pipe pollution minimization, but then gradually moving towards pollution prevention (Dornfeld, 2013). Another stream of activities concerned the increasing need for reduction of waste, remanufacturing of products as well as recycling and reuse (Sarkis and Rasheed, 1995). These developments are reflected in *Scientific American*, e.g. in the use of keywords such as 'pollution control' or 'recycling' (Fig. 6B and C). Interestingly, the term 'recycling' was first intensively used during WWII, returning to the discussion after the 1970s (see also Appendix B). This suggests that either the meaning of this term was different during two periods, or that wartime considerations temporarily promoted a practice that was widely adopted later on. However, similarly to the digitalization stream, very little evidence could be found of more recent principles such as aiming to secure green production inputs, recovering used products from the customer or designing production in order to

Table 3
Summary of qualitative and quantitative evidence for the propositions of the DT framework.

Theoretical proposition	The historical development of mass production *Qualitative evidence*	*Quantitative evidence*
GESTATION (before the 4th surge) Before the surge, rules emerge and compete in several niches of individual socio-technical systems without much coordination	**1765–1907** Emergence of different principles in various niches (e.g. food processing, bicycle industry, mining, military), including partial alignment (e.g. the American System of Manufacturing)	**1765–1907** Evidence of rules related to work organization and new technologies (e.g. interchangeability, electrification) Little evidence of principles related to labour control
INSTALLATION (4th surge) **Irruption:** emerging and incumbent rules and regimes come to compete against each other in individual systems, resulting in transitions	**1908–1919** Transition in the mobility system: emergence of mass production regime (Henry Ford) and its competition with scientific management Early extension of mass production to other systems (e.g. defence, food) accelerated by World War I	**1908–1919** Evidence of some rules part of mass production (e.g. 'move work to worker') Evidence of competing rule-sets (mass production vs. scientific management), extending to both phases
Frenzy: rules increasingly cross the boundaries of single systems and partially align to each other, leading to the formation of alternative, possibly competing rule-sets	**1920–1938** Development of mass production toward increased flexibility (General Motors's 'flexible mass production'), regional variations in Europe Further extensions and varying attempts to apply mass production in new systems (e.g. communication, housing)	**1920–1938:** Evidence of rules part of mass production and the mass production rule-set itself Very little evidence of General Motors's technical improvements
TURNING POINT (4th surge) Tipping of the scales decisively in favour of one meta-regime that becomes dominant	**1939–1945** Amplification and extension of mass production (e.g. tanks, ships, uniforms), coupled with experiments with flexible production (e.g. airplanes)	**1939–1945** Evidence of wartime peaks for several rules (e.g. interchangeability, electrification, moving work to worker) as well as the mass production rule-set itself No evidence of experiments with flexible production
DEPLOYMENT (4th surge) **Synergy:** the dominant meta-regime selects niches compatible with its logic, diffuses to various systems and starts to shape the landscape	**1946–1959** Societal embedding of American-style mass production, including the 'Americanization' of Europe Further development of mass production in two directions (automation in USA, Toyota's experiments in Japan)	**1946–1959** Contrary evidence: keywords related to rules underlying mass production as well as the mass production rule-set itself start to decrease Evidence of automation but nothing on Japanese experiments
Maturity: the dominant meta-regime loses its grip and the cycle re-starts with other niches, systems and rules becoming central to the new surge	**1960–1972** Further consolidation and deepening of mass production, but also first signs of maturation (offshoring, USA) Gradual maturation of automation and Toyota's production	**1960–1972** Continued decrease in the frequency of occurrence of rules related to mass production (both single rules and rule-sets) Dip in automation, no evidence of Japanese experiments
INSTALLATION (5th surge) The framework makes no propositions about the behaviour of mature surges during the emergence of the next one	**1973–2018** The crisis of dominant version of mass production provokes attempts to optimize it (neofordism) and to reconfigure it in three directions: reorganization of work (primarily 'lean production'), digitalization and greening	**1973–2018:** Very little evidence on neofordism Some evidence of digitalization (single rules and rule-sets) and greening of production (e.g. pollution control, recycling) but virtually nothing on more recent developments (e.g. mass customization, peer production, sustainable production) Virtually no evidence on Japanese lean production

Source: Authors' elaboration.

minimize the environmental impacts of the product during its entire life-cycle (Sarkis et al., 2011; Garetti and Taisch, 2012; Johansson and Sundin, 2014; Drohomeretski et al., 2015).

5. Discussion

5.1. Evidence for the propositions of the deep transitions framework

We start by comparing the theoretical propositions of the DT framework to the qualitative evidence. Using the latter as a baseline for interpretation, we then assess the extent to which the quantitative evidence generated by the text mining analysis aligns with the qualitative storyline. The results are presented in Table 3.

Based on our findings, we can draw three specific lessons. First, whereas qualitative evidence is largely in line with the theoretical propositions, quantitative evidence offers a sketchier picture, being partially or sometimes entirely absent (see Section 5.2 for possible reasons). However, where evidence exists, it generally supports the qualitative results. This is especially evident in Fig. 4 which illustrates multiple propositions of the DT framework simultaneously, e.g. the competition between the emerging meta-regime and its competitors (mass production vs. scientific management), the importance of the turning point (mass production peaking during WWII) as well as the succession of mass production by the next surge focused on ICT-s (automation, digitalization).

Second, contrary to initial expectations, we found that the deployment period was characterized by a decrease in the use of keywords representing mass production. On one hand, this can be seen as a falsification of our expectations. On the other hand, this finding can be interpreted as the 'normalization' of the meta-regime; that is, in the post-war era mass production had become a standard mode of production and as such the novelty of the associated terms started to decrease. The latter rationale is in line with what is reported by culturomics studies (e.g. Cristianini et al., 2018; Iliev et al., 2016; Lansdall-Welfare et al., 2017; Michel et al., 2011). These studies have pioneered the use of text mining to examine the evolution of human culture relying both on evidence from newspapers- and books-based corpora. These studies have provided evidence that the frequency of some terms tend to follow particular patterns characterised by a period of 'pre-celebrity' with a following rise, a peak, and then a decline (e.g. Michel et al., 2011). Also, the pace and temporal accuracy of these patterns depend on the nature of the examined source: for example, given the focus on reporting novel information in a timely manner, newspapers provide a more accurate temporal representation of major historical shifts than books, which are instead more reflective in nature and less bounded by the timing of events (Lansdall-Welfare et al., 2017). *Scientific American* is more similar to newspapers than books given the frequency of publication (i.e. weekly, then monthly) and the focus of this source on new discoveries and inventions. On this basis, we expect *Scientific American* to behave similarly to newspaper sources in relation to the rise and decline of keywords associated with rules. However, distinguishing between historical dead-ends and commonplace solutions on the basis of a single text corpus remains a major methodological

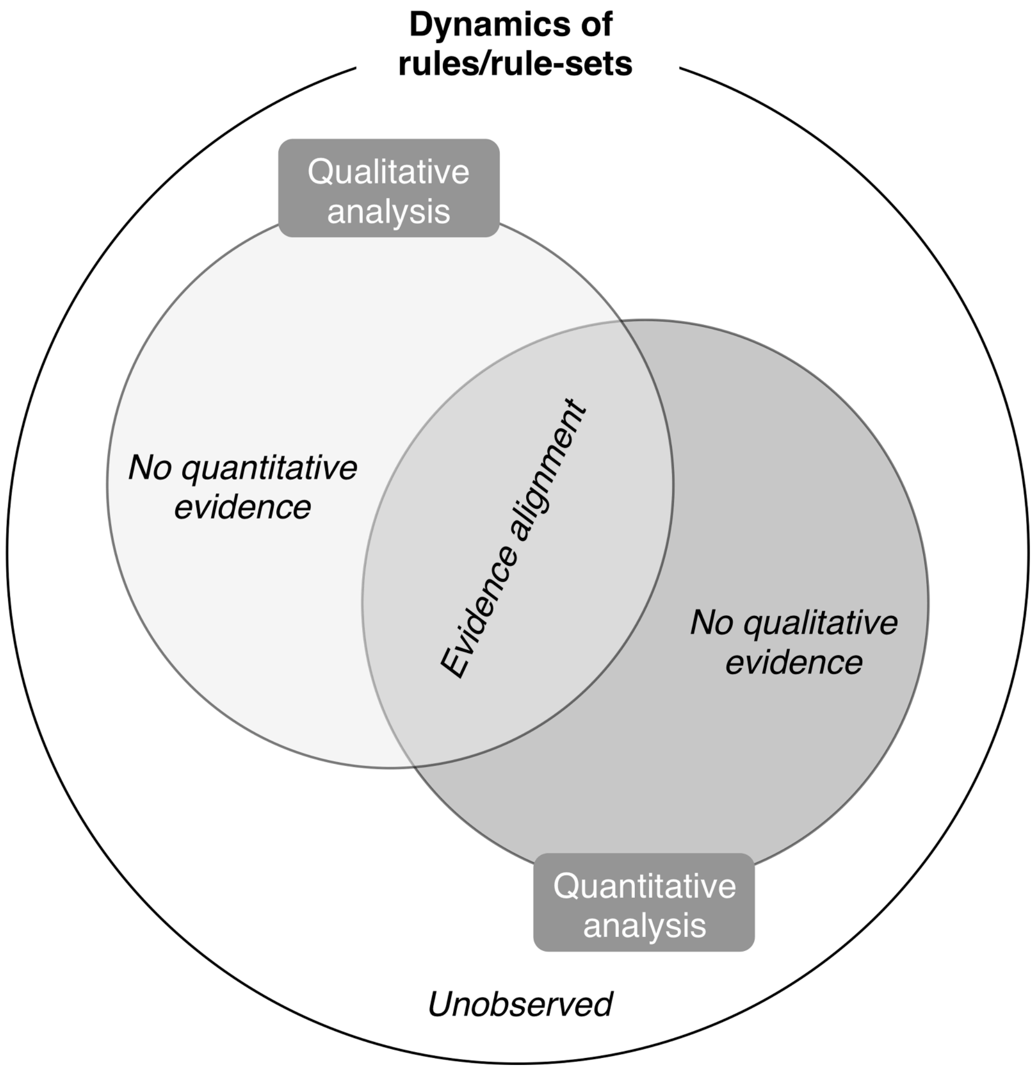

Fig. 7. Convergence between qualitative and quantitative analysis. *Source: Authors' elaboration.*

challenge. This is because both might show a similar pattern of ascendance and decline. To address this methodological limitation, future work could use the triangulation of qualitative narratives, multiple text sources, and data about the diffusion of inventions (e.g. historical patent data) (see Section 5.2 for more details).

Third, our analysis of mass production in the last 50 years partly confirms Perez's suggestion that mature meta-regimes continue to develop through further optimization or 'rationalization' (2002: 154) as evidenced by neofordist attempts to relocate production. However, we find this to be only part of the story as the crisis of American-style mass production also included considerably more ambitious responses in various countries such as placing more emphasis on the humanization of work, attempts to make production 'leaner', digitalization of industry and greening of production. Furthermore, our analysis shows that many of these attempts can be traced back already to the synergy phase (Toyota in the 1940s, automation in the 1950s). We therefore propose that the crisis of the mature meta-regime does not only stimulate the emergence of a new surge but also an internal transformation of the existing meta-regime. In particular, internal transformation of the formerly dominant meta-regime will likely occur before the transformative impact of the meta-regime associated with the next surge. This is because of the time (20–30 year long installation period) required for the formation of a new meta-regime and the maturation of associated technological opportunities. That would explain why, despite the presence of both automation and 'lean' directions already in the 1940s-1950s, mass production was first transformed by lean production, followed by the (still ongoing) digitalization of industry.

Overall, we find our first research question - to what extent are the evolutionary patterns proposed by the Deep Transitions framework manifest in empirical data? - to be largely supported by historical data. That is, the evolution of rules constituting mass production largely conform to the patterns hypothesized in Schot and Kanger (2018). However, our study has also made it possible to extend the existing framework by adding a further proposition concerning the evolutionary dynamics of post-surge meta-regimes.

5.2. Methodological lessons

The results presented in Section 4 largely focused on instances where quantitative findings aligned with the qualitative narrative. We will now focus on divergence between the two approaches (see Fig. 7) and the possible reasons underlying this.

At times text mining provided no evidence of the dynamics expected from the qualitative analysis. More specifically, many of the keywords selected to identify these rules and rule-sets occurred at low levels of frequency providing limited scope for longitudinal mapping. The ability to observe longitudinal trends requires repeated use of keywords over a number of years which depends on the size of the corpus, the focus of the source compared to the concepts to be observed, and how keywords have permeated common language. Thus, the absence of such keywords in the text corpus does not necessarily imply that the associated rules were absent. For example, some keywords might be too technical and hence unlikely to occur frequently in a journal with general orientation. This might have been the case for keywords such as 'time and motion study', 'managerial control', and 'micromotion studies' explaining why little evidence was found for rules such as 'separate planning from execution' or 'optimize a single task'.

Every source has its own topical and geographical bias which affects its content. *Scientific American* is more likely to focus on American rather than international trends, including reporting on mass production. This is well illustrated by the case of 'lean production': very few keywords associated with this rule-set could be identified in the source, and keywords such as 'toyotism' and 'toyota production system' were completely absent in the corpus. Similarly, the content of a source evolves over long periods of observation. For example, change in the focus of *Scientific American* from a technology-orientated journal to a science-orientated magazine likely explains why the quantitative analysis provided limited evidence on neofordism.

Another source of misalignment between qualitative and quantitative analysis were various language issues introducing noise to the analysis. For example, some acronyms have multiple meanings (e.g. CAM can stand for 'computer aided manufacturing' but also various technical devices), which can create mismatches especially for the earlier observation period where the quality of the print may induce the OCR not to recognize all letters accurately. While acronyms can reveal patterns of consolidation of a technology (Reardon, 2014), their use could be problematic if not carefully assessed. Therefore, in our study, we eventually decided to exclude all acronyms (e.g. CAD, CAM, 3R, 4R, DFA, DFM). In other cases, keywords turned out to have other uses besides the expected ones. For instance, we observed a number of occurrences of the word 'robot' around the 1930s. Upon manual checking, we discovered a discussion around the definition of the term, which was not related to the use of robots in mass production.

In summary, it seems that the quantitative approach yielded better results on (i) rules containing a strong technical component (e.g. interchangeable components, electrification, assembly line) vs. rules related to work process organization and labour control (e.g. the absence of management-related trends during gestation, or neofordism from the late deployment); (ii) rules related to American developments vs. rules introduced elsewhere (e.g. the virtual lack of Japanese advances); (iii) historical vs. more recent rules (e.g. the lack of newer ideas on digitalization of manufacturing and sustainable production); (iv) rule-sets vs. specific rules (see Fig. 4 on the overall storyline).

Based on the foregoing discussion we propose to broaden and extend future studies on long-term socio-technical systems change in four directions. The first extension is to employ additional techniques of analysis. The measurement of word frequencies conducted in this paper was based on the assumption that a rule can be captured with a term or a combination of terms. However, for some rules this assumption may not hold. For example, a general term may acquire a more specific meaning only when discussed with other terms. The co-occurrence of particular keywords in the same article, and thus the deployment of co-word analysis, is likely to be more suitable for detecting certain rules. Future research could also consider Natural Language Processing approaches that go beyond the bag-of-words model. In particular, NLP techniques of syntactic parsing can detect the elements of a sentence such as nouns and verbs, and dependencies amongst these (Feldman and Sanger, 2006). This approach could provide an empirical base to identify a more comprehensive set of patterns of how rules emerge in the text corpus of a source. It is, however, worth noting that synthetic parsing cannot be applied to a source such as *Google Books* as data are currently accessible only in the form of n-grams rather than sentences. Furthermore, the occurrence of a keyword in the corpus of a source does not inform us on the debate around the rule the keyword is representing. Sentiment analysis can be used to assess whether a rule is discussed in a positive, neutral, or negative manner. This could be treated as an indicator of the changing contestation of rules, meta-rules, regimes and meta-regimes.

A second extension is the use of co-occurrence analysis to shed light on how rules diffuse within and across socio-technical systems. This requires delineating *thesauri* of terms capable of capturing portions of text relating to socio-technical systems (e.g. energy, food, mobility, healthcare) in a longitudinal manner since the components of socio-technical systems and their descriptions are likely to evolve when the observation period spans several decades. The co-occurrence of terms within these *thesauri*, with keywords related to a given rule, could signal and provide evidence of (i) the socio-technical systems in which the rule first emerges, (ii) impacts of the emerging rule on particular elements of the systems, (iii) the pace with which the rule diffuses across systems, (iv) whether this diffusion process occurs in sequence or simultaneously across systems (as well as with other rules), and (v) the emergence of multi-system interactions. These analyses could also provide possibilities for developing a taxonomy of rules depending on diffusion patterns observed in textual data.

The third extension is to expand the set of sources in terms of genres and geographical coverage. In particular, the text mining of daily and weekly newspapers would allow the capture of social and cultural dimensions of rule change. One may also consider adding sources which are more clearly identified with particular industrial sectors, i.e. trade journals (provided they are available in digitized format). This would allow the timing of the relative incidence of keywords to be compared across industries and between different sources. For example, one might assume a time-lag between the introduction of 'assembly line' in trade journals, general science and technology journals, and daily newspapers.

Fourth, the results of our study are also a call for a collective effort to build a research data infrastructure that includes multiple text corpora as well as a set of complementary tools to support the use of such data. These include metadata that characterize each source in several dimensions (e.g. history, format, and audience) as well as *thesauri* for analysis and classification purposes. If the sustainability transitions research community would engage in building up a larger corpus, as well as metadata and a set of tools to study the corpus, it could be used for multiple studies.

As a response to our second research question - how can the complex co-evolutionary and long-term patterns of Deep Transitions be studied? - we therefore conclude that the proposed mixed method approach indeed opens up promising new opportunities for studying single- and multi-system transitions, both historical and ongoing. For more contemporary studies, the selection of suitable text sources is likely to be less problematic because of the proliferation of digitised source data.

6. Conclusion

In this paper we develop a new mixed method approach for exploring the propositions of the Deep Transitions framework. Combining a qualitative historical case study with a quantitative mapping of rules, based on the interpretive analysis of secondary literature and the measurement of word frequencies in the text corpus of *Scientific American* respectively, we traced the co-evolution of rules underpinning mass production from the 18th century to the present. We find that the qualitative narrative provides relatively strong support for the propositions of the framework, whereas evidence from quantitative mapping was more limited yet still supportive (see Table 3). Our comparative analysis between *Scientific American* and *Google Books* also suggests that text data available in *Google Books* can be used for a preliminary exploratory analysis notwithstanding its limitations (e.g. a lack of metadata about the composition of the source). Our research also extends the Deep Transitions framework by making a new proposition on the evolutionary dynamics of mature post-surge meta-regimes. Furthermore, our approach offers a number of lessons about the strengths and limitations of text mining applied to the study of complex, long-term and co-evolutionary dynamics of socio-technical systems change.

Most importantly, our study opens up a new research avenue for researching single system shifts, multi-system interactions and Deep Transitions. Follow-up studies can explore other dimensions of the mass production meta-regime – cultural or business dimensions – by focusing on other sources. They can also look at other meta-regime transitions – such as from linear to circular production, or from carbonized to carbon neutral production – and focus on regimes of single systems or multiple systems using a shorter time period. Another option is to explore the spatial dimension by using sources from different languages. We recognize that for a historical study the availability of sources still poses a real, albeit a constantly decreasing constraint as more and more sources are digitized. Combining qualitative interpretive work with quantitative text mining to assess the prospects for a Second Deep Transition therefore constitutes another promising direction of future work.

Funding

This work was supported by James Anderson and Baillie Gifford & Co.

CRediT authorship contribution statement

Laur Kanger: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Frédérique Bone:** Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Daniele Rotolo:** Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **W. Edward Steinmueller:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Johan Schot:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Acknowledgements

This work was supported by James Anderson and Baillie Gifford & Co. The paper has been discussed with several colleagues at the International Sustainability Transitions 2019 conference and in a series of workshops, including the Deep Transitions research team and invited guests. We would like to thank David Nye, Phil Scranton and Carlota Perez for their informative comments, criticisms and suggestions on previous versions of this paper.

Appendix A. Notes on constructing the genealogy of rules

Constructing a genealogy of mass production is based on a close reading of multiple textual sources: mainly secondary historical literature in this study (but also including a few primary sources). The close reading entails a constant comparison and contrasting of observations made in different sources. The continuous interpretation of these texts means an iterative shifting between the descriptions of specific production technologies, practices and principles, some limited generalizations based on these descriptions (both made by the authors of various studies), and higher-order abstractions reflecting the broader commonalities of the previous two (made by the analyst). This process entailed four basic analytical moves: (1) identification of rules; (2) grouping of rules; (3) determining the 'appropriate' degree of granularity for the rules, and; (4) specifying the timing of rules. The following will use examples from different texts to illustrate each move.

I. Identification of rules

The first stage of interpretive work is to sort out what counts as a rule. Consider the following passages from three works discussing the history of mass production (note that here and below underlining has been done by the authors of the Appendix):

- "Although British visitors to the United States in the 1850s, especially Joseph Whitworth and John Anderson, were impressed with every aspect of American manufacturing, small arms production received their most careful and detailed analysis. … In his report, Anderson indicated that the federal armoury at Springfield had indeed achieved what the Ordnance Department had sought since its inception: true interchangeability of parts" (Hounshell, 1985: 4).
- "A second idea essential to the assembly line was that of interchangeability of parts that fit smoothly together without the need for any last-minute sanding, filing, or polishing. The origin of this idea can be traced back at least as far as the early eighteenth century" (Nye, 2013: 24).
- "Fred Colvin's article … summarizes some of his key findings from a series of 15 technically detailed studies of Ford's Highland Park factory, subsequently published in the *American Machinist.* … The keys to this [Ford's system], Colvin shows, were the rigour of interchangeability, strict standardization, sequential organization of production flow, dedicated and innovative specialized tooling, and the radical simplification of tasks, all of which were in place *before* the assembly line" (Tolliday, 1998: xiii-xiv).

These quotes yield two important pieces of information about the evolution of mass production. First, all of them underscore the importance of interchangeability as an essential component of mass production. Second, they indicate that the idea of interchangeability has a long history, predating the emergence of mass production for more than a century. One should also take into account that all the works quoted above are authoritative: the first two are monographs by eminent historians of technology, whereas the third one is a 2-volume anthology of writings on mass production which includes both contemporary articles as well as historical literature.

Based on the above one can therefore conclude that a rule around the notion of interchangeability should be recognized as one of the core rules of mass production. What remains to be done is to word it as such, i.e. 'make components interchangeable'.

II. Grouping of rules to rule-sets

A separate but related task is to sort out what counts as a rule-set. Here the interpretive focus shifts from the identification of single rules to the identification of production principles that occur together under a more general label (e.g. American System, Ford's mass production). Generalized statements in different studies are often helpful for this purpose:

- "Mass production of automobiles, as developed by Henry Ford in the half-dozen years before the First World War, depended on three basic principles: the standardization of the product, the use of special-purpose equipment, and the elimination of skilled labour in direct production" (Tolliday and Zeitlin, 1987: 153).

- "These five practices – subdivision of labour, interchangeable parts, single-function machines, the sequential ordering of machines, and the movement of work to the man via slides and belts – together define the assembly line as a physical technology. A sixth factor, factory electrification was a necessary precondition before these elements could be improved individually and welded together into a new form of production" (Nye, 2010: 70).
- "The keys to this [Ford's system], Colvin shows, were the rigour of interchangeability, strict standardization, sequential organization of production flow, dedicated and innovative specialized tooling, and the radical simplification of tasks, all of which were in place *before* the assembly line" (Tolliday, 1998: xiii-xiv).

These three definitions have substantial overlaps: (1) all of them highlight the importance of specialized machinery and detailed division of labour; (2) the first and the third definition share an emphasis on standardization; (3) the second and the third definition share emphases on interchangeability and sequential machine placement. The most recent definition by David E. Nye highlights two other components, moving work to worker and electrification, discussing their importance in detail. The importance of the latter two principles is also stressed in other studies, e.g. Geels, 2006b analysing the role of electrification in the transition of a factory production regime.

Based on the above one can therefore be fairly certain that the following rules constitute the core of the mass production regime/meta-regime: (1) make components interchangeable; (2) delegate single tasks to single machines; (3) arrange machines according to the sequence of work; (4) move work to worker; (5) electrify factories, working environments and machines; (6) standardize products; (7) divide production into specific tasks to be carried out by a specific worker.

III. Granularity of rules and rule-sets

A third operation is to choose the appropriate level of granularity on which the rules and rule-sets are formulated. This effectively implies deciding which formulations are too generic to be of use (i.e. too vague to be detected with particular keywords in text mining and/or not enabling to make distinctions between varieties of mass production) and which ones too specific (and hence unlikely to be detected via text mining). Since this level of granularity cannot be determined in advance with much certainty, the formulation involves intuition and guesswork. Nevertheless it is possible to demonstrate the basic analytical reasoning at work here through a few examples:

- Henry Ford defines mass production: "Mass production is not merely quantity production, for this may be had with none of the requisites of mass production. Nor is it merely machine production, which also may exist without any resemblance to mass production. Mass production is the focussing upon a manufacturing project of the principles of power, accuracy, economy, system, continuity, and speed" (Ford, 1926: 157).
- David A. Hounshell discussing how General Motors approached mass production: "In this consciously orchestrated economy of change and consumption that stressed style and comfort above utility, mass production as Ford had developed it with the T was no longer suitable. The ground rules had changed. The Ford Model T dictum of maximum production at minimum cost gave way to planning for change. … This was the era of "flexible mass production"" (Hounshell, 1985: 264).
- Yasuhiro Monden defines Toyota's production system: "In brief, a continuous flow production is created by achieving two key concepts: *Just-in-Time* and *Autonomation.* These two concepts are the pillars of the Toyota production system. *Just-in-Time* basically means to produce the necessary units in the necessary quantities at the necessary time. *Autonomation* may be loosely interpreted as autonomous defects control" (Monden, 1981a: 135–136).
- Yasuhiro Monden describes Toyota's production system: "In order to shorten the setup time, four major concepts must be first recognized … *Concept No. 1: Separate the internal setup from the external setup. … Concept No. 2: Convert as much as possible of the internal setup to the external setup. … Concept No. 3: Eliminate the adjustment process. … Concept No. 4: Abolish the setup step itself*" (Monden, 1981b: 26–28).

Whereas the first quote by Henry Ford explicitly outlines some underlying principles of mass production, notions like power, accuracy or speed are too vague and generic as these arguably characterize any form of production before or after mass production. In contrast, the quote by Hounshell attempts to pinpoint the crucial difference between Ford and General Motors. One of the distinctive features of the latter can be worded as 'design production for regular product change'. Such an approach enables distinguishing between varieties of mass production (fordist vs. flexible). As such it is more granular than Ford's own definition and also more useful for analytical purposes, enabling to trace the evolution of the mass production meta-regime over time.

Quotes 3 and 4 describe the underlying principles of Japanese lean production as practised by Toyota. Here the third quote identifies its two key features, whereas the fourth one focuses on production setup. As shown on the accompanying figure (Monden, 1981a: 137) short setup time constitutes only part of the overall smoothing of production, itself part of four elements (along with the design of processes, standardization of jobs and *kanban*) contributing to just-in-time production. As an additional consideration, it is unlikely that the source chosen for text mining (*Scientific American*) would contain extensive and sustained coverage on technical details of production. Therefore, the rules in quote 4 are too granular as the distinctiveness of lean production from its predecessors can be formulated on a higher level of abstraction: 'provide supplies exactly when/where required'.

IV. Timing of rules and rule-sets

The final task concerns the placement of rules and their combinations on the timeline. Here too, a close reading of the sources provides important clues:

- "The quest for interchangeability of parts … grew out of eighteenth-century French military rationalism. … Beginning in 1765 [Jean-Baptiste de] Gribeauval sought to rationalize French armaments by introducing standardized weapons with standardized parts" (Hounshell, 1985: 25).
- At the Rifle Works, two important streams of development in manufacturing technology flowed together into a major stream that runs through American history. There, the idea ofuniformity or interchangeability of parts was combined with the notion that machines could make things as good and fast as man's hands, or even better. The result of this combination was the method of production usually called the "American system of manufacture" … (Hounshell, 1985: 43).

- "Although this [Siegfried Giedion's historical] interpretation of Ford deserves careful attention, it underestimates the singular importance of the changes made at the Ford factory in 1913 and 1914 (as well as how they came about) and the way these changes were rapidly diffused throughout the Western world. … Fordism, a word coined to identify the Ford production system and its concomitant labour system, changed the world" (Hounshell, 1985: 218).

The first quote dates one possible origin for the rule 'make parts interchangeable'. It is chosen as a starting point of the narrative because Hounshell is able to demonstrate how French experiments were mediated to the Americans through various channels (1985: 25–28). The second quote summarizes the essence of the American System which was about connecting interchangeability to mechanized production. This quote can be found in a chapter titled "The American System in the Antebellum Period". The context of the discussion makes it quite clear that by the mid-19th century American production had matured to such an extent that it was recognized as a novelty by foreign observers (see the quote on British visitors in Section I). The third one highlights the crucial role of experimentation in Ford's factory around 1913–1914, when various production principles were brought together into a mass production regime for the first time.

The combination of these four analytical strategies enabled a gradual move from source-specific descriptions to a full genealogy, consisting of 45 rules and 9 rule-sets.

Appendix B

Table B1

Rules and occurrences of keywords in the text corpus of *Scientific American*. A keyword frequency is reported in parentheses.

Rule Id	Rule description	Occurrence *higher than* 0.0001% of the text corpus	Occurrence *lower than* 0.0001% of the text corpus	No occurrences
1	Use hand tools for making the products	fitters (262)	craft production (12)	artisanal manufacturing
2	Make parts interchangeable	gauges (11,673) interchangeability (4344) specification (17,373) standardization (768) tolerance (2655)	reproducibility (83)	
3	Delegate single tasks to single machines	fixtures (6056)	single-purpose machines (10) special-purpose equipment (12) special-purpose machines (29)	single-function equipment* single-function machines
4	Arrange machines according to the sequence of work		operator station (50) machine tool arrangement (1) plant layout (52) process chart (6)	machine tool placement* sequencing of machines
5	Move work to worker	assembly line (489) continuous-process (253) conveyor (3371)	bridge crane (25) continuous movement (81) gravity feed (62)	continuous-flow production
6	Electrify factories work environments and machines	electric arc lighting (224) electric drive (1065) electric motor (6872) electrification (1000) ventilation (5733)		
7	Optimize the work process as a whole	operation analysis (170)	plant layout (52) production engineering (91)	factory layout man and machine chart
8	Standardize products		model year (38) product standardization (1) product type (34) standardization of products (1) standardized products (7)	
9	Divide production into specific tasks to be carried out by a specific worker	operation analysis (170)	division of jobs (1) division of labour (8) division of tasks (2) labour specialisation (4) process analysis (58) task definition (3)	
10	Separate planning from execution		managerial control (4)	time and motion study
11	Optimize a single task		task optimization (1) micromotion studies (7) motion economy (17)	
12	*Re*-use waste from production		utilization of scrap (2) utilization of waste (27)	utilization of leftovers
13	Minimize waste in production		minimization of waste (4) reduction of waste (15) waste elimination (6) waste minimization (4)	elimination of waste waste reduction
14	Design production for regular product change		annual model change (5) instalment purchasing (3) dynamic obsolescence (1) planned obsolescence (13)	instalment sales built-in-obsolescence
15	Employ common components across different products	chassis (2504)	product family (21)	product platform
16	General purpose machinery should be tailored to specific tasks		british system (48)	custom machine design middle-range machine* semi-specialized machine*

(*continued on next page*)

Table B1 (*continued*)

Rule Id	Rule description	Occurrence *higher than* 0.0001% of the text corpus	Occurrence *lower than* 0.0001% of the text corpus	No occurrences
17	Use materials and processes that increase the speed of operations	high speed steel (178) injection moulding (187) pneumatic tools (241)		
18	Design production for continuous product and process improvement	fine tuning (141)	continuous improvement (23) process refinement (34) kaizen (2) total quality control (3)	six sigma
19	Anyone should be able to stop production upon spotting an error		autonomation (1)	fishbone analysis jidoka production levelling
20	Provide supplies exactly where/when required		kanban (6)	jit supply* just-in-time supply
21	Tap worker expertise for production improvement		employee involvement (8) quality circles (7) quality control circles (7)	employee creativity employee suggestion boxes employee suggestion rewards* employee suggestion schemes
22	Design products so they would be easy to manufacture		manufacturability (8)	assembly evaluation method design for assembly design for manufacturing
23	Maintain close and cooperative relations with external actors		procurement management (1) supplier management (19) supplier partnership (4)	first tier supplier
24	Organise production in teams of multi-skilled workers		cellular manufacturing (2) multi-tasking (18)	multi-skilling multifunctional teams
25	Workers should be able to choose the pace of execution			dock assembly standstill production group assembly system* team assembly system*
26	Decouple production from consumption		automobile imports (16) automobile trade (46) deindustrialization (14)	
27	Internationalise parts supply		international subsidiaries (1)	global parts logistics* global value chains international procurement intra-industry trade
28	Execute production globally and in real time		real-time execution (1) real-time operation (8)	globalization of manufacturing globalization of production internationalization of manufacturing internationalization of production real-time planning
29	Minimize human intervention in machine-environment feedback loop	computer-aided or integrated design (149) robotics (1333) robots (3816)	automated production management (3) computer-aided or integrated engineering (3) computer-aided or integrated manufacturing (37) numerical control (73)	automated performance management automated product control or automated production control
30	Employ rapid changeover machines		flexible manufacturing (22) flexible production (9) rapid changeover (1)	flexible specialisation
31	Design for modularity	skids (469)	modular components (14) modular design (73) modularity (60)	modularization
32	Design and produce to customer specifications		built-to-order (2) configuration systems (43) configurators (1)	made-to-order
33	Employ common and customized components			delayed product differentiation open product architecture product family architecture
34	Design production for rapid change in structure/control		agile manufacturing (5) rapid manufacturing (20)	reconfigurable manufacturing system cyber-physical system industry 4.0
35	Employ common customized and personalized components			personalized production open product platform* personalized components
36	Design for personal preferences produce on demand		personalized design (1)	on-demand manufacturing on-demand manufacturing systems* hyper-personalization*
37	Repair and upgrade products on a constant basis			product lifetime extension product repairability product upgradeability*
38	Design global manufacture local		collaborative design (15) digital commons (2) fab lab (4)	open design communities* open design movement*

(*continued on next page*)

Table B1 (*continued*)

Rule Id	Rule description	Occurrence *higher than* 0.0001% of the text corpus	Occurrence *lower than* 0.0001% of the text corpus	No occurrences
			local manufacturing (62) open-source hardware (3)	
39	Minimize end-of-pipe industrial pollution	pollution control (302)	catalytic converter (93) reducing engine displacement (2)	end-of-pipe gasahol petrol additives
40	Prevent pollution and industrial waste		clean technology (15) cleaner production (5) pollution prevention (49) source prevention (3) source reduction (4) waste prevention (12)	
41	Remanufacture products from used components	recovering (1270)	refurbishing (19) remanufacturing (12)	
42	Reuse and recycle materials and products	recycling (776)	recyclability (4) reusability (9) reusing (32)	
43	Design to minimize environmental impact during the whole life-cycle		eco-design (1)	cradle-to-cradle design cradle-to-grave design* environmentally conscious design life-cycle engineering life-cycle planning regenerative design sustainable design
44	Move used products back to the customer			aftermarket logistics aftermarket supply chain closed-loop logistics retrogistics* reverse logistics reverse supply chain
45	Secure green production inputs		clean energy supply (2) green purchasing (1)	green inputs green procurement

* Keywords that have no occurrences in *Google Books,* all other keywords in the table are also found in the *Google Books* corpora. *Source: Authors' elaboration.*

Table B2
Rule-sets and occurrences of keywords in the text corpus of *Scientific American*. A keyword frequency is reported in parentheses.

Rule-set Id	Rule-set description	Occurrence *higher than* 0.0001% of the text corpus	Occurrence *lower than* 0.0001% of the text corpus	No occurrences
1	American System of Manufacturing	mass manufacturing (589)	large-scale manufacturing (47)	american system of manufactures / american system of manufacturing american system of production
2	Systematic management	scientific management (162)	systematic management (5) taylorism (1)	
3	Fordism	mass production (1411)	fordism (5) mass consumption (6) sloanism (3)	flexible mass production
4	Lean production		lean manufacturing (4) lean production (6)	just-in-time manufacturing just-in-time production toyota production system toyotism
5	Digitalization	automation (1087) digitalization (10,202)	smart manufacturing (2)	modular manufacturing modular production smart production
6	Mass customization		mass customization (3)	mass customized manufacturing mass customized production
7	Personalization			mass personalization personalized manufacturing
8	Green production	circular manufacturing (131)	green manufacturing (10)	circular production closed-loop manufacturing closed-loop production green production

Source: Authors' elaboration.

Appendix C

We conducted a robustness analysis that longitudinally compared the frequency of keywords associated with the rules of mass production as emerging from the text corpus of *Scientific American* with trends emerging from *Google Books*. We retrieved frequency data from *Google Books* for all keywords using the R package "ngramr" (https://github.com/seancarmody/ngramr). We detected a larger proportion of keywords (92% of 213 keywords associated with rules) in the corpus of *Google Books* than using *Scientific American* text data. More precisely, all the keywords that were detected in *Scientific American* were also detected in *Google Books*. Also, 70 keywords with no instances in *Scientific American* were identified in *Google Books* data, while 17 keywords were found in none of the two text corpora (see Appendix B for details). The ability of *Google Books* to detect such a wide

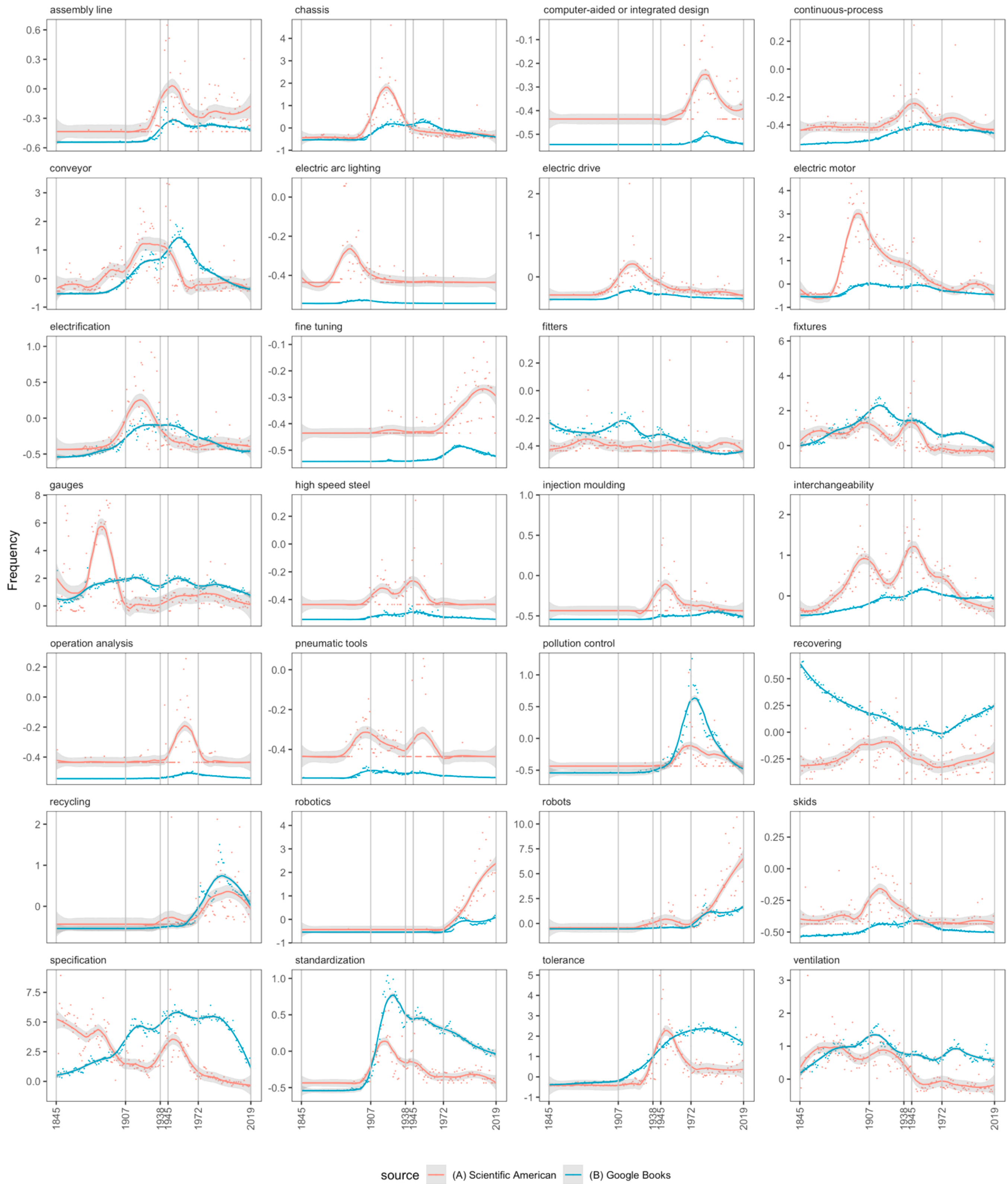

Fig. C1. Time series of the keywords representing the rules associated with mass production as emerging from the text corpora of *Scientific American* and *Google Books*. Keywords representing at least 0.0001% of the text corpus of *Scientific American* are depicted. Frequencies are calculated using a 5-year moving time window, normalised by the size of the text corpus, and standardised for comparison purposes. Trend lines are estimated using locally smoothed regression (LOESS) – the grey bands represent 95% confidence intervals around smooth. Key years delineate the gestation, installation, turning point and deployment of the 4th surge, and the 5th surge in chronological order. *Source: Authors' elaboration.*

Table C1
Results of the Granger causality test (lag = 5 years, *p-value* < 0.05): keywords and proportion of keywords for each case.

Keywords		*Google Books* **Granger-causes** *Scientific American*		
		Yes		No
Scientific American **Granger-causes** *Google Books*	Yes	(i) 15/28 keywords (54%)		(ii) 2/28 keywords (7%)
		Chassis	*Operation analysis*	*Conveyor*
		Computer-aided or integrated design	*Pollution control*	*Interchangeability*
		Electric arc lighting	*Robotics*	
		Electric drive	*Robots*	
		Electric motor	*Skids*	
		Electrification	*Standardization*	
		High speed steel	*Tolerance*	
		Injection moulding		
	No	(iii) 6/28 keywords (21%)		(iv) 5/28 keywords (18%)*
		Assembly line		*Continuous-process*
		Fine tuning		*Fitters*
		Fixtures		*Gauges*
		Pneumatic tools		*Recovering*
		Recycling		*Ventilation*
		Specification		

*With lags of 1–10 years in the Granger causality test, the number of keywords for which the two sources are misaligned ranges from 4 to 6.
Source: Authors' elaboration.

array of keywords could be mostly attributed to the sheer size of this text corpus which is about 20,000 times larger than *Scientific American*.

However, for a meaningful comparison and in line with the analysis presented in the paper, we focus on keywords representing at least 0.0001% of the text corpus of *Scientific American*, i.e. keywords that occurred at least 97 times. This constitutes a sample of 28 keywords. Although in certain instances the relative frequency of keywords in *Scientific American* and *Google Books* is substantially different (see Fig. C1), our objective is to compare trends, i.e. to understand if and in which cases growth and decline of keywords align across the two sources. The comparison time series was therefore performed on the basis of the Granger (predictive) causality test (Granger, 1969; Stock and Watson, 2001). More precisely, we tested for the extent to which the lagged frequency time series of a keyword in one source Granger-causes the frequency time series of the same keyword in the other source. We used a lag of 5 years although results are qualitatively the same for shorter or longer lags. It is worth noting that our aim is not to test for causal links between the two sources, but to understand whether two frequency time series relate to each other since one time series improves the prediction of the other time series.

The analysis revealed four possible cases as outlined in Table C1: (i) the lagged frequency time series of a keyword in *Scientific American* Granger-causes the frequency time series of the same keyword in *Google Books* and vice versa; (ii) the lagged frequency time series of a keyword in *Scientific American* Granger-causes the frequency time series of the same keyword in *Google Books*, but there is no statistical evidence for the opposite; (iii) the lagged frequency time series of a keyword in *Google Books* Granger-causes the frequency time series of the same keyword in *Scientific American*, but there is no statistical evidence for the opposite; (iv) the lagged frequency time series of a keyword in *Scientific American* does not Granger-cause the frequency time series of the same keyword in *Google Books*, and vice versa. We argue that cases (i), (ii), and (iii) represent instances where the temporal pattern of a keyword is similar in *Scientific American* and *Google Books* although in the same cases a temporal lag exists. The time series misaligns in case (iv).

Table C1 summarises the keywords and the proportion of keywords falling in each quarter – the Granger (predictive) causality test was considered significant with a *p-value* <0.05. The two sources align across 82% of the keywords we examined although there are instances where one source seems to provide early signals of emergence – e.g. "interchangeability" in the case of Scientific *American* and "assembly line" in the case of *Google Books*. Although the sources suggest different trends in the case of five keywords, the overall analysis provides evidence of robustness regarding the qualitative-quantitative analysis presented in the paper.

References

Alder, K., 1997. Innovation and amnesia: engineering rationality and the fate of interchangeable parts manufacturing in France. Technol. Cult. 38 (2), 273–311.

Barron, A.T.J., Huang, J., Spang, R.L., DeDeo, S., 2018. Individuals, institutions, and innovation in the debates of the French Revolution. PNAS 115 (18), 4607–4612.

Beniger, J.R., 1986. The Control Revolution: Technological and Economic Origins of the Information Society. Harvard University Press, Cambridge.

Biggs, L., 1995. The engineered factory. Technol. Cult. 36 (2), 174–188.

Creswell, J.W., Plano Clark, V.L., 2018. Designing and Conducting Mixed Methods Research.

Cristianini, N., Lansdall-Welfare, T., Dato, G., 2018. Large-scale content analysis of historical newspapers in the town of Gorizia 1873–1914. Hist. Methods A J. Quant. Interdisc. Hist. 51 (3), 39–164.

Dornfeld, D.A. (Ed.), 2013. *Green Manufacturing: Fundamentals and Applications*. Springer Science & Business Media, New York.

Drohomeretski, E., da Costa, S.E.G., de Lima, E.P., de Oliveira Neves, T.R., 2015. The Application of sustainable practices and performance measures in the automotive industry: a systematic literature review. Engineering Management Journal 27 (1), 32–44.

Ericson, A.-S., 1970. An analysis of Mexico's border industrialization program. Monthly Labor Review 93 (5), 33–40.

Feldman, R., Sanger, J., 2006. The Text Mining Handbook. Cambridge University Press, Cambridge.

Fogliatto, F.S., da Silveira, G.J.C., Borenstein, D., 2012. The mass customization decade: an updated review of literature. Int. J. Prod. Econ. 138, 14–25.

Freeman, C., Louçã, F., 2001. As Time Goes By: From the Industrial Revolutions to the Information Revolution. Oxford University Press, Oxford.

Fröbel, F., Heinrichs, J., Kreye, O., 1980. The New International Division of Labour: Structural Unemployment in Industrialized Countries and Industrialization in Developing Countries. Cambridge University Press, New York.

Fuenfschilling, L., Truffer, B., 2014. The structuration of socio-technical regimes – Conceptual foundations from institutional theory. Res. Policy 43 (4), 772–791.

Fürstenberg, K., 2016. Evolutionary institutionalism: new Perspectives. Polit. Life Sci. 35 (1), 48–60.

Genus, A., Coles, A.-.M, 2008. Rethinking the multi-level perspective of technological transitions. Res. Policy 37 (9), 1436–1445.

Garetti, M., Taisch, M., 2012. Sustainable manufacturing: trends and research challenges. Production Planning & Control 23 (2–3), 83–104.

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems. Insights about dynamics and change from sociology and institutional theory. Res. Policy 33 (6–7), 897–920.

Geels, F.W., 2005. Technological Transitions and System Innovations: A Co-Evolutionary and Socio-Technical Analysis. Edward Elgar, Cheltenham, UK.

Geels, F.W., 2006a. The hygienic transition from cesspools to sewer systems (1840–1930): the dynamics of regime transformation. Res. Policy 35 (7), 1069–1082.

Geels, F., 2006b. Major system change through stepwise reconfiguration: a multi-level analysis of the transformation of American factory production (1850-1930). Technol. Soc. 28, 445–476.
Geels, F.W., 2007. Analysing the breakthrough of rock'n'roll (1930-1970): multi-regime interaction and reconfiguration in the multi-level perspective. Technol.l Forecast. Soc. Change 74 (8), 1411–1431.
Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environmental Innovation and Societal Transitions 1 (1), 24–40.
Geels, F.W., Schot, J., 2010. The dynamics of socio-technical transitions: a socio-technical perspective. In: Grin, J., Rotmans, J. (Eds.), Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change. J. Schot in collaboration with F. W. Geels, D. Loorbach., New York, Routledge, pp. 11–101.
George, A.L., Bennett, A., 2005. Case Studies and Theory Development in the Social Sciences. The MIT Press, Cambridge, MA.
Giddens, A., 1984. The Constitution of Society: An Outline of a Theory of Structuration. Polity Press in association with Basil Blackwell, Oxford.
Gordon, R.J., 2016. The Rise and Fall of American Growth. Princeton University Press, Princeton & Oxford.
Granger, C.W., 1969. Investigating causal relations by econometric models and cross-spectral methods. Econometrica 37 (3), 424–438.
Grin, J., Rotmans, J., Schot, J., 2010. Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change. Routledge, New York.
Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 2, 173–184.
Hiteva, R., Watson, J., 2019. Governance of interactions between infrastructure sectors: the making of smart grids in the UK. Environ. Innov. Soc. Trans. 32, 140–152.
Holweg, M., 2007. The genealogy of lean production. J. Oper. Manag. 25, 420–437.
Hounshell, D., 1985. From the American System to Mass Production, 1800-1932: The Development of Manufacturing Technology in the United States. The Johns Hopkins University Press, Baltimore, ML.
Hu, S.J., 2013. Evolving paradigms on manufacturing: from mass production to mass customization and personalization. Proced. CIRP 2013, 3–8.
Iliev, R., Hoover, J., Dehghani, M., Axelrod, R, 2016. Linguistic positivity in historical texts reflects dynamic environmental and psychological factors. Proc. Natl. Acad. Sci. 3 (49), E7871–E7879.
Intergovernmental Panel on Climate Change. 2018. Global Warming of 1.5 °C. Special Report. Available online: https://www.ipcc.ch/sr15/.
Johansson, G., Sundin, E., 2014. Lean and green product development: two sides of the same coin? Journal of Cleaner Production 85, 104–121.
Johnstone, P., McLeish, C., 2020. World wars and the age of oil: Exploring directionality in deep energy transitions. Energy Research & Social Science 69, 101732.
Kaiser, W., Schot, J., 2014. Writing the rules for Europe. Cartels, experts and international Organizations. Basingstoke, Hampshire: Palgrave Macmillan.
Kanger, L., Schot, J., 2019. Deep Transitions: theorizing the long-term patterns of socio-technical change. Environ. Innov. Soc. Trans. 32, 7–21.
Kanger, L., Sillak, S., 2020. Emergence, consolidation and dominance of meta-regimes: exploring the historical evolution of mass production (1765-1972) from the Deep Transitions perspective. Technol. Soc. 63, 101393.
Kapoor, R., Klueter, T., 2020. Progress and setbacks: the two faces of technology emergence. Res. Policy 49 (1), 103874.
Kelly, B., Papanikolaou, D., Seru, A., Taddy, M., 2020. Measuring technological innovation over the long run. Natl. Bur. Econom. Res. Work. Paper Ser. 25266.
Kern, F., Sharp, H., Hachmann, S., 2020. Governing the second deep transition towards a circular economy: How rules emerge, align and diffuse. Environmental Innovation and Societal Transitions 37, 171–186.
Kim, N., Lee, H., Kim, W., Lee, H., Suh, J.H, 2015. Dynamic patterns of industry convergence: evidence from a large amount of unstructured data. Res. Policy 44 (9), 1734–1748.
Klingenstein, S., Hitchcock, T., DeDeo, S., 2014. The civilizing process in London's Old Bailey. Proc. Natl. Acad. Sci. 111 (26), 9419–9424.
Kogan, L., Papanikolaou, D., Seru, A., Stoffman, N., 2017. Technological innovation, resource allocation, and growth. Q. J. Econ. 132 (2), 665–712.
Köhler, J., Geels, F.W., Kern, F., Markard, J., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Nykvist, B., Onsongo, E., Pel, B., Raven, R., Rohracher, H., Sanden, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., 2019. An agenda for sustainability transitions research: state of the art and future directions. Environ. Innov. Soc. Trans. 1, 1–32.
Kohlrausch, M., Trischler, H., 2014. Building Europe on Expertise: Innovators, Organizers, Networkers. Palgrave Macmillan, London.
Koplenig, A., 2017. The impact of lacking metadata for the measurement of cultural and linguistic change using the Google Ngram data sets. Reconstructing the composition of the German corpus in times of WWII. Digit. Scholarsh. Humanit. 32 (1), 169–188.
Konrad, K., Truffer, B., Voß, J.P., 2008. Multi-regime dynamics in the analysis of sectoral transformation potential: evidence from German utility sectors. J. Clean. Prod. 16 (11), 1190–1202.
Kostakis, V., Niaros, V., Dafermos, G., Bauwens, M., 2015. Design global, manufacture local: exploring the contours of an emerging productive model. Futures 73, 126–135.
Krafcik, J., 1988. Triumph of lean production system. Sloan Manag. Rev. 30 (1), 41–52.
Landes, D.S., 2003. The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present, 2nd ed. Cambridge University Press, Cambridge, UK.
Lansdall-Welfare, T., Sudhahar, S., Thompson, J., Lewis, J., FindMyPast Newspaper Team, F.N., Cristianini, N., 2017. Content analysis of 150 years of British periodicals. Proc. Natl. Acad. Sci. 114 (4), E457–E465.
Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field and its prospects. Res. Policy 41 (6), 955–967.
McShane, C., 1997. The Automobile: A Chronology of Its Antecedents, Development, and Impact. Fitzroy Dearborn Publishers, London.
Michel, J.B., Shen, Y.K., Aiden, A.P., Veres, A., Gray, M.K., Pickett, J.P., Hoiberg, D., Clancy, D., Norvig, P., Orwant, J., Pinker, S., 2011. Quantitative analysis of culture using millions of digitized books. Science 331 (6014), 176–182.
Milanovic, B., 2016. Global Inequality: A New Approach for the Age of Globalization. Harvard University Press, Cambridge, MA.
Mokyr, J., 2017. Culture of Growth: The Origins of the Modern Economy. Princeton University Press, Princeton, NJ.
Muffatto, M., 1999. Evolution of production paradigms: the Toyota and Volvo cases. Integr. Manuf. Syst. 10 (1), 15–25.
Nye, D.E., 2013a. America's Assembly Line. The MIT Press, Cambridge, MA.
Oreskes, N., Conway, E.M., 2020. Unlimited information is transforming society. Sci. Am. 1 September 2020.
Papachristos, G., Sofianos, A., Adamides, E, 2013. System interactions in socio-technical transitions: extending the multi-level perspective. Environ. Innov. Soc. Trans. 7, 53–69.
Pechenick, E.A., Danforth, C.M., Dodds, P.S, 2015. Characterizing the google books corpus: strong limits to inferences of socio-cultural and linguistic evolution. PLOS ONE 10 (10), e0137041.
Perez, C., 2002. Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages. Edward Elgar, Cheltenham, UK.
Perez, C., 2010. Technological revolutions and techno-economic paradigms. Camb. J. Econ. 34 (1), 185–202.
Pettit, M., 2016. Historical time in the age of big data: cultural psychology, historical change, and the Google Books Ngram Viewer. Hist.f Psychol. 19 (2), 141–153.
Petralia, S., Balland, P.A., Rigby, D.L, 2016. Unveiling the geography of historical patents in the United States from 1836 to 1975. Sci. Data 3 (1), 160074.
Reardon, S., 2014. Text-mining offers clues to success. Nature 509, 410.
Raven, R.P.J.M., Verbong, G.P.J., 2007. Multi-regime interactions in the dutch energy sector. The case of combined heat and power in the Netherlands 1970-2000. Technol. Anal. Strateg. Manag. 19 (4), 491–507.
Raven, R.P.J.M., Verbong, G.P.J, 2009. Boundary crossing innovations: case studies from the energy domain. Technol. Soc. 31 (1), 85–93.
Rip, A., Kemp, R., 1998. Technological change. In: Rayner, S., Malone, E.L. (Eds.), Human Choice and Climate Change. Battelle Press, Columbus, OH, pp. 327–399.
Rodgers, D.T., 1998. Atlantic Crossings: Social Politics in a Progressive Age. &The Belknap Press of Harvard University Press, Cambridge, MALondon, UK.
Rosenbloom, D., 2020. Engaging with multi-system interactions in sustainability transitions: a comment on the transitions research agenda. Environ. Innov. Soc. Transitions 34, 336–340.
Rule, A., Cointet, J.P., Bearman, P.S, 2015. Lexical shifts, substantive changes, and continuity in State of the Union discourse, 1790–2014. Proc. Natl. Acad. Sci. 112 (35), 10837–10844.
Sarkis, J., Rasheed, A., 1995. Greening the manufacturing function. Bus. Horiz. 38 (5), 17–27.
Sarkis, J., Zhu, Q., Lai, K.H., 2011. An organizational theoretic review of green supply chain management literature. International Journal of Production Economics 130 (1), 1–15.
Schot, J., Kanger, L., 2018. Deep transitions: emergence, acceleration, stabilization and directionality. Res. Policy 47 (6), 1045–1059.
Schröter, H.G., 2007. Economic Culture and Its Transfer: americanization and European Enterprise, 1900-2005. Rev. Écon. 58 (1), 215–229.
Sebestyén, V., Domokos, E., Abonyi, J, 2020. Focal points for sustainable development strategies - Text mining-based comparative analysis of voluntary national reviews. J. Environ. Manag. 263 (1), 110414.
Sewell, W.H., 1992. A Theory of Structure: duality, Agency, and Transformation. Am. J. Sociol. 98 (1), 1–29.
Smith, M.R., 1977. Harpers Ferry Armory and the New Technology: The Challenge of Change. Cornell University Press, Ithaca, NY.
Sorrell, S., 2018. Explaining sociotechnical transitions: a critical realist perspective. Res. Policy 47 (7), 1267–1282.
Stock, J.H., Watson, W.W, 2001. Vector Autoregressions. J. Econ. Perspect. 15 (4), 101–115.
Stearns, P.N., 2013. The Industrial Revolution in World History, 4th edition. Westview Press, Boulder, CO.
Stefaner, M., Daston, L., Christiansen, J., 2020. The language of science: how the words we use have evolved over the past 175 Years. Sci. Am. 1 September 2020.
Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., de Wit, C.A., Folke, C., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223), 736–746.
Sutherland, L.-A., Peter, S., Zagata, L., 2015. Conceptualising multi-regime interactions: the role of the agriculture sector in renewable energy transitions. Res. Policy 44 (8), 1543–1554.
Svensson, O., Nikoleris, A., 2018. Structure reconsidered: towards new foundations of explanatory transitions theory. Res. Policy 47 (2), 462–473.
Trentmann, F., 2016. Empire of Things. How We Became a World of Consumers, from the Fifteenth Century to the Twenty-First. HarperCollins Publishers, New York.

Van den Bergh, J.C.J.M., Truffer, B., Kallis, G., 2011. Environmental innovation and societal transitions: introduction and overview. Environ. Innov. Soc.l Trans. 1 (1), 1–23.
Zeitlin, J., 1995. Flexibility and mass production at war: aircraft manufacture in Britain, the United States, and Germany, 1939-1945. Technol. Cult. 36 (1), 46–79.
Zeitlin, J., Herrigel, G, 2000. Americanization and Its Limits: Reworking US Technology and Management in Post-War Europe and Japan. Oxford University Press, New York.
Zolfagharian, M., Walrave, B., Raven, R., Romme, A.G.L., 2019. Studying transitions: past, present, future. Res. Policy 48 (9), 103788.
Yin, R.K., 2018. Case Study Research and Applications, 6th edition. Sage, London.
Ford, H. 1926. Mass production. Encyclopaedia Britannica, 13th edition, Volume 15: 38–41. Reprinted in S. Tolliday (ed.), The Rise and Fall of Mass Production, Vol. 1, Cheltenham, UK, Edward Elgar, 157-163.
Monden, Y., 1981a. What makes the Toyota production system really tick? Ind. Eng. 135–146. January: 36, 38-40, 42-44, 46. Reprinted in S. Tolliday (ed.), The Rise and Fall of Mass Production, Vol. 2, Cheltenham, UK, Edward Elgar,.
Monden, Y., 1981b. How Toyota shortened supply lot production time, waiting time and conveyance time. Ind. Eng. 2, 147–155. September: 22-30. Reprinted in S. Tolliday (ed.), The Rise and Fall of Mass Production, Cheltenham, UK, Edward Elgar.
North, D., 1990. *Institutions, Institutional Change and Economic Performance.* UniversityPress, Cambridge: Cambridge.
Nye, D.E., 2010. What was the assembly line? Tidsskr. Hist. 1 (1), 59–81.
Nye, D.E., 2013. America's Assembly Line. The MIT Press, Cambridge, MA.
Tolliday, S., Zeitlin, J, 1987. Between fordism and flexibility: the automobile industry and its workers – past, present and future. Archiv. Sozialgeschicte 231–249. XXVIII: 153-171. Reprinted in S. Tolliday (ed.), The Rise and Fall of Mass Production, Vol. 1, Cheltenham, UK, Edward Elgar,.
Tolliday, S., 1998. The Rise and Fall of Mass Production, 2 Volumes. Edward Elgar, Cheltenham, UK.

Laur Kanger is a research fellow in sustainability transitions studies in the Science Policy Research Unit, University of Sussex, and a senior research fellow in technology research in the Institute of Social Studies, University of Tartu. In addition to being one of the authors of the Deep Transitions framework, he has also conducted research on user roles in transitions, societal embedding of radical innovations, energy justice in transitions and policy interventions in systems change.

Frédérique Bone (formerly Lang) is Research Fellow at SPRU, University of Sussex. She is an active researcher in the field of Research of Research and research evaluation. A strong interest of hers is to understand research collaboration through the development of new methods taking advantage of both quantitative and qualitative aspects. She is applying data science, machine learning and natural language processing tools to study, and create a longitudinal understanding of technological development using bibliometrics and news article data.

Daniele Rotolo is Senior Lecturer in Science, Technology and Innovation Policy at SPRU, University of Sussex. His-most recent work has focused on the phenomenon of corporate science, the conceptualisation and operationalization of emerging technologies, inter-organisational network dynamics featuring technological change, and scientometric mapping techniques.

W. Edward Steinmueller is a Professor of Information & Communication Technology Policy at SPRU, University of Sussex. He has published widely in the field of the industrial economics of information and communication technology industries including integrated circuits, computers, telecommunications, software and the economic and social policy issues of the Information Society. He has also contributed to research in science policy and the economics of basic research.

Johan Schot is Professor of Comparative Global History at the Utrecht Centre for Global Challenges, University of Utrecht. He has conducted research on history of technology, Dutch history, European history, constructive technology assessment, innovation policy and sustainability transitions. Together with Laur Kanger he is one of the developers of the Deep Transitions framework.