Aggregation activities

Local and global dynamics in technological development: a socio-cognitive perspective on knowledge flows and lessons from reinforced concrete

Frank Geels and J Jasper Deuten

Although knowledge flows are a popular concept, the underlying dynamics are not well understood. This article develops a perspective that conceptualises the social and cognitive activities that make knowledge flows possible. Dynamics involve interactions between local and global levels, and dedicated aggregation activities by intermediary actors. An idealtypical four-phased pattern is developed to understand the creation of global knowledge. The socio-cognitive perspective is illustrated with a historical case study, the emergence of reinforced concrete (1850–1940). The concluding section formulates policy implications for nurturing the emergence of radically new technologies.

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KNOWLEDGE FLOWS IN NETWORKS are important in literatures on clusters, innovation systems and knowledge management. But these literatures leave open the question *how* knowledge can actually flow. In fact, the metaphor suggests that knowledge is something discrete, like a fluid, which can flow. But these literatures neglect the socio-cognitive activities that make it possible for knowledge to flow, that is, the creation of generic knowledge and its circulation. This article addresses that lacuna, conceptualising knowledge flows as local-global activities of dis-embedding and re-embedding. Before articulating the specific research question, the article introduces the theoretical debate in sociology of technology about local and global levels in technological development.

Anthropological and ethnographic scholars see technological development as a site-specific, contingent, messy and local process (Latour and Woolgar, 1979; Turnbull, 1993). To make technologies work in *local* practices requires the mobilisation and alignment of heterogeneous elements, for example, skills to work machines and instruments, workers, funding, problem solving. Because technologies must work on location, technological knowledge tends to be local. Other scholars point at *global* knowledge that is more generic and shared between actors in a technical community. Evolutionary economists study ‘technological regimes’ (Nelson and Winter, 1982), the shared cognitive routines (e.g. search heuristics, exemplars), which guide and

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orient engineer's activities in a technical community. Although engineers work in different local practices, their shared cognitive routines explain why they collectively work in the same direction, resulting in technological trajectories at the community level.

For similar purposes social constructivists coined the term 'technological frame', which consists of problem agendas, problem-solving strategies, search heuristics, theories, testing procedures, and design methods and criteria (Bijker, 1995). Rip (1997: 616) used the term "cosmopolitan knowledge", which he described as having "more formal and abstract features compared to the local practices from which it emerged and to which it might apply (e.g. law-like statements, handbook data, rules of thumb, standardised metrologies and charts)". In a literal sense, cosmopolitan knowledge is knowledge that is no longer tied to its original context; it has been delocalised and can be made to work in various localities.

Hård (1994) has tried to combine these two contrasting views, arguing that the global level of general shared beliefs, orientations and schemas does not determine action in local practices. Actors have much space to respond to the uniqueness of events in concrete situations. Local practices and global orientations have a dialectical relationship: "We would treat engineering work as a social activity, a practice that includes both abstract and concrete elements, both *universal knowledge* and *embodied skills*" (Hård, 1994: 573; italics in original). Local design choices are the outcome of both global orientations and local circumstances (e.g. local networks of financers and component suppliers). Although Hård (1994) aims to combine local and global levels, he gives prevalence to the local level and practitioners:

> A practice approach should bring forth the technician as tinkerer (following the 'logic of practice') rather than the engineer as theoretician, and technology as *bricolage* (informed by 'practical sense') rather than engineering as knowledge production. (p. 574; italics in original)

In our view, however, Hård (1994) downplays the importance of global knowledge too much. Furthermore, his idea about the dynamics of global knowledge is too simple:

> If we discuss the development of technology, then we ought to focus on the specific inclinations of engineering practitioners active within a *local network*, and treat general developments in terms of patterns that can be observed *ex post* (in particular *global trajectories*) … A technological trajectory depicts the collective outcome of actions taken by the practitioners in a field. (p. 573; italics in original)

Instead of viewing global knowledge as something that simply emerges from local practices and can only be observed *ex-post*, we argue that global knowledge is an achievement that involves dedicated cognitive work. Various types of 'intermediary actors' are involved in aggregating knowledge from local practices. Against this background the article addresses the following question: How can we conceptualise the process of creating shared technical knowledge? More specifically, how is local knowledge transformed into global knowledge?

To answer these questions, the next section describes an idealtypical four-phased conceptual perspective. We then illustrate this perspective with a historical case study: the emergence of reinforced concrete (1850–1940). Lastly, we draw conclusions and discuss policy implications.

Aggregation and intermediary actors

Local practices form the place of origin of novelty and new technical knowledge. New technologies emerge as small technical steps in response to local problems, and only later give rise to new technical trajectories. Thus, both new artefacts and knowledge emerge through localised work. But local technical knowledge does not simply flow to other locations, as if it were a discrete entity. Before knowledge can circulate, it has to be made sufficiently context-free. This is one of the central issues in the sociology of *scientific* knowledge: How can knowledge created in a laboratory be made to work in other laboratories, and outside laboratories in 'real-life' contexts (Rouse, 1987; Latour, 1999)? For the sociology of *technical* knowledge, this question of how knowledge can be made to work in other places is similarly relevant. To create generic knowledge that can circulate, dedicated socio-cognitive work is needed to bring about a process of aggregation. 'Aggregation' is the process of transforming local knowledge

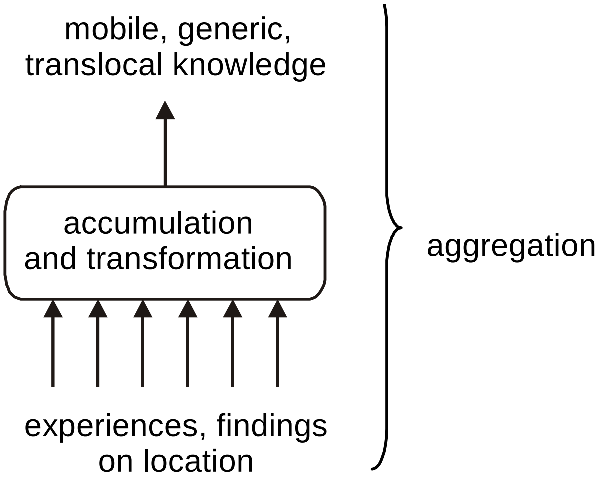

Figure 1. Aggregation of knowledge
Source: Deuten (2003: 50)

into robust knowledge, which is sufficiently general, abstracted and packaged, so that it is no longer tied to specific contexts. This global knowledge can travel between local practices (Figure 1).

Typical aggregation activities include standardisation, model building, writing of handbooks, formulation of best practices. Also codification, a term used by economists to describe the transformation of tacit into codified knowledge, is part of aggregation:

> Typically, a piece of knowledge initially appears as purely tacit — a person has an idea ... As it is explored, used and better understood, less of it remains idiosyncratic to a person or few people, and more of it is transformed into some systematic form that can be communicated at low cost ... As the principles underlying the piece of knowledge come to be understood, they can be written down ... This, again, is a process by which tacit knowledge becomes codified. (Cowan and Foray, 1997)

Codification means recording in a 'codebook' and involves model building, language creation and message writing. While codification highlights the 'coding' aspect of dynamics, aggregation also emphasises the 'de-localisation' aspect. Aggregation refers to a broader socio-cognitive process of which codification is an aspect.[1]

Aggregation entails the production of a collective good: abstract knowledge that can be used by others. Because of free-rider problems, participation in aggregation processes is not self-evident. Why would you contribute to the build-up of a collective knowledge reservoir and share experiences with others, especially when they are competitors? Without proper arrangements or incentive structures, such collective goods will not be produced optimally, because they can be used by others who have not contributed to its production (Deuten, 2003). An important arrangement is the creation of intermediary actors, for example, professional societies, industry associations, standardisation organisations. Such intermediary actors may be created when actors perceive themselves as part of an emerging community with collective interests. In that case, perceived benefits of producing a collective good may outweigh perceived disadvantages.

Intermediary actors may perform aggregation activities, because they have special responsibilities and roles. Standardisation organisations, for instance, are responsible for creating and maintaining a collective reservoir of (standardised) technical knowledge (Schmidt and Werle, 1998). Professional societies and industry associations also stimulate and facilitate the production and circulation of technical knowledge. They may create technical standards, articulate problem agendas, and exchange experiences and findings to further the interests of the (emergent) field *as a whole*. Also firms that travel between local practices may aggregate knowledge. Engineering firms or sector research institutes, for instance, are hired by other firms to perform certain jobs. They can compare experiences in different locations, reflect on differences and draw general conclusions. They can use this aggregated knowledge for other jobs in different locations. Initially, they may aggregate their experiences for intra-organisational purposes only. But they may also be willing to share (parts of) their knowledge reservoirs to enhance their reputation and visibility in relevant forums.

Aggregation activities by intermediary actors do not revolve around finding technological solutions for local, specific problems, but rather around the creation, maintenance and distribution of generic, abstracted knowledge that can be used throughout a technological field (Rip, 1997; Deuten, 2003). So there is a division of cognitive labour: practical technical work in local practices, and dedicated aggregation activities to transform local experiences into global knowledge. Intermediary actors work at this global level. `Intermediary actors are not always present from the start. They are often created as part of the emergence of a new technical community. Also the creation of an infrastructure for circulation and aggregation processes is important. Such an infrastructure consists of forums that enable (and

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induce) the gathering and interaction of actors, the exchange of experiences and the organisation of collective action. Examples of such forums are conferences, seminars, workshops, technical journals, proceedings, and so on. The creation of these forums tends to be part of community formation processes.

Using these considerations, we propose a dynamic socio-cognitive perspective on the creation of global technological knowledge. Following Deuten (2003) and Deuten and Rip (2005), we distinguish four phases that differ in: the social groups involved, their interaction and networks; the kind of cognitive activities performed by social groups. The perspective is socio-*cognitive*, because it distinguishes different cognitive activities, varying from problem solving in local practices to knowledge circulation and aggregation. The perspective is *socio*-cognitive because it encompasses different social groups, networks, struggles and conflict (because of economic interests related to knowledge development). The development of global knowledge is a non-linear process, consisting of four phases.

In the first, *local* phase, new technologies emerge in one or more local practices that are relatively independent and create knowledge for their own purposes. This knowledge tends not to be shared with others. There is no dedicated infrastructure for circulation, no forums where people can interact and exchange knowledge. There is no global level at which actors are engaged in making knowledge robust and available for others. In this phase, interactions are limited and knowledge remains local. Inventors and innovative producers operate relatively independently from each other, developing novelties in response to local problems and local demand. Consequently, local variety in technological forms and knowledge is high. Gradually, local actors may become aware of each other (e.g. word of mouth). Some interactions may take place, for example, limited discussions of future prospects or limited competition.

The second, *inter*-local phase is characterised by increasing circulation of technological knowledge within networks, alliances and supplier–producer relations. Typically, firms try to build such networks to support their own version of the technology. Different networks may be formed around competing technical designs. Knowledge remains proprietary within the network and is not disclosed to outsiders. Learning and accumulation of experiences has an (inter)local character. Groups of firms in a network may try to raise the reputation and legitimacy of their product to broaden their market. Circulation of papers, documents and people becomes more important. Experts will venture outside their local practices to hold talks at meetings and meet with possible clients. Producers of the technology increasingly interact with other producers, suppliers, users and regulators. Small markets emerge, which form an incentive for producers to work towards stabilisation of knowledge and quality standards.

This second phase ends when demands on performance increase in terms of reliability, safety, quality and/or operability. Demanding customers, for instance, may ask that technological performance is underpinned by 'sound', broadly accepted, engineering knowledge. Producers can anticipate on such demands through modelling, comparing best practices and the identification of overall design guidelines. Because this involves comparisons between local practices and drawing of more generic lessons, it forms an incentive for the shift to the third phase.

The third, *trans*-local phase is characterised by increased production and circulation of knowledge that is not intended for use in specific local practices, but rather for the field as a whole (e.g. handbooks, articles). This phase is also characterised by the emergence of intermediary actors. Groups of firms may recognise collective interests and set up professional associations or industry associations to speak for the new field as a whole. The intermediary actors perform dedicated knowledge *activities* at the global level, aimed at creating, maintaining and distributing a collective knowledge repertoire, for example, standardisation efforts in standardisation committees (Schmidt and Werle, 1998).

This phase also sees the emergence of a knowledge infrastructure for the circulation of knowledge, for example, the creation of dedicated journals, organisation of workshops and conferences. A distribution of cognitive labour emerges between local and global knowledge activities. A substantial part of knowledge production becomes disembedded from specific local practices and their idiosyncratic contexts. Global-level work towards stabilisation of generic knowledge is important, because it enables broader market penetration. Mainstream users outside niche markets tend to have high performance demands in terms of reliability, safety and interoperability. This implies that quality standards and safety regulations have to be underpinned by theoretical knowledge, technological models and systematically gathered experimental data. Intermediary actors help to define best working practices, develop guiding principles and coordinate scientific research. The outcome of these socio-cognitive dynamics is visible in the standardisation of a shared dominant design.

A transition to a fourth, *global* phase occurs when institutionalisation and standardisation result in the establishment of dominant cognitive rules. Global knowledge is standardised in codes, standards, handbooks and textbooks, creating a collective knowledge reservoir. A reversal occurs, in which collective knowledge repertoires at the global level become guiding for local-level activities. Local practices become part of a stabilised global technological regime, from which it is hard to deviate. Institutionalisation also occurs in the form of dedicated courses and training programs.

These four phases are schematically represented in Figure 2.

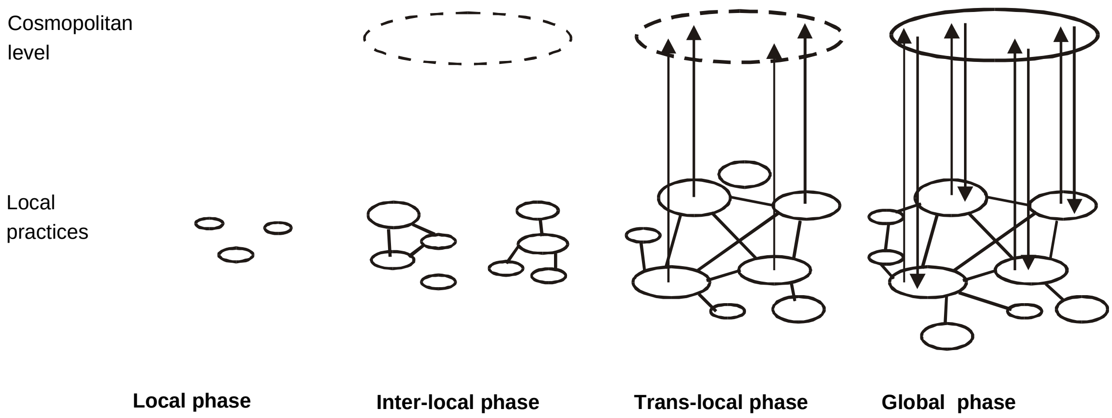

Figure 2. Phases in the development of shared technological knowledge
Source: Deuten (2003); Raven (2005)

Case study

To illustrate the socio-cognitive perspective, this section presents a historical case study, the emergence of reinforced concrete from 1850 to 1940 (based on Deuten, 2003). Reinforced concrete, at the time a novel combination of concrete and iron, started in the mid-19th century as a heterogeneous set of local technologies without much knowledge of underlying technical principles. By the early 20th century, reinforced concrete had become a global technology with stable design rules and shared knowledge repertoires. The following sub-sections analyse this development from local to global knowledge.

Local phase (1850s–1870s)

Reinforced concrete technology started as local solutions for specific problems with traditional constructional materials (wood, bricks, iron). Early forms of reinforced concrete included substitutes for wooden, rot-susceptible flowerpots, water reservoirs and rowing boats. Various inventors experimented with reinforcing concrete pots and reservoirs with iron wire to prevent structures from cracking. Other forms of reinforced concrete were iron building elements encased by concrete to make them fire-resistant, and concrete-iron substitutes for expensive natural stone (Deuten, 2003). Local actors operated independently and created their own knowledge to serve their purposes.

Early applications of iron–concrete artefacts remained limited to distinct applications with venturing customers who highly valued the waterproofness, fire-proofness and inexpensiveness of the new building material. In the 1860s, inventive entrepreneurs developed complete building systems based on novel combinations of iron and concrete. Patents were issued for concrete–iron elements such as pipes and reservoirs (patented in 1868), flat slabs (1869), bridges and footbridges (1873), stairs (1875), and floor constructions (1878).

An inventive and entrepreneurial ‘system’ owner was the Frenchman Joseph Monier who took a universal patent on his ‘Monier system’ in 1878. He subsequently sold licences to constructors in Germany, Austria, England and Belgium. This licensing helped to spread his system within a closed network. This system was “backed up neither by theory nor by systematic experiment” (Elliot, 1992: 172). Knowledge was produced through trial-and-error, guided by ‘constructional sense’ rather than by theoretical insights. Monier’s construction systems were based on intuitions, not calculations, that concrete and iron could play complementary roles: while concrete took the compressive stresses, iron took the tensile stresses.

Knowledge had a local character: if the iron–concrete mixture or climatic conditions were different from normal due to local circumstances, the performance of the reinforced concrete construction became unpredictable and unreliable. Also indicative of the local character was the fact that German licensees hired French experts who had worked with Monier’s system. Thus, parts of reinforced concrete knowledge on did not ‘travel’ well through time nor space.

To attract attention to their novelties, system owners and licensees disclosed part of their knowledge. They organised demonstrations and performed public tests with their structures, for instance by burdening them with excessive loads. But such tests could not demonstrate durability over time, which remained a contested issue. It was feared that minute cracks in the concrete could lead to rusting of the embedded iron, resulting in collapses. Despite these uncertainties, venturing customers were interested in reinforced concrete because of advantages in fire-resistance and shock-proofness.

The local phase came to an end when reinforced concrete entrepreneurs wanted to enter mainstream markets in the building sector. To get permissions and meet building regulations, they had to improve their formal knowledge base to make performance more calculable.

Inter-local phase (1870s–1890s)

From the 1870s to the 1890s, new systems emerged besides the Monier system, protected by patents. Technological ingenuity and commercial strategy were important in the ensuing 'battle of systems'. To enter the mainstream building sector, reinforced concrete entrepreneurs had to develop new knowledge and master the technology. To improve the understanding of their proprietary systems, system owners and their licensees accumulated and exchanged experiences *inside* their social network. But knowledge production remained system-specific, and circulation beyond the network of licensees was limited. There were also technical reasons that limited knowledge transfer between systems: the varieties of reinforced concrete consisted of different mixtures of materials and positioning of iron reinforcements. On his tour of Europe, an American engineer, Colby, identified no less than 144 systems (Colby, 1909). Rivalry between system owners was high, and they kept their knowledge secret. Technological details and tricks of the trade were not shared with rivals, and patents were protected with vigorous litigation (Cusack, 1987). With limited circulation, knowledge remained system-specific.

A first step in the creation of global knowledge occurred in the Monier network, which had expanded patent licensing. One of his licensees was Wayss, an ambitious German constructor interested in the commercial possibilities of reinforced concrete in buildings. He had to deal with relatively strict German building regulations. Authorities were not easily convinced of the reliability and durability of the new material. The lack of formal, generic knowledge meant that the strength of constructions could not be reliably calculated beforehand. Furthermore, there was uncertainty about possible cracking of the concrete and rusting of iron reinforcements. To secure permission from the building inspectorate, Wayss performed an extensive testing programme in the 1870s, supervised by Koenen, an appointed *Regierungsbaumeister*. Tests showed that heat expansion coefficients of iron and concrete were practically the same, implying that concrete and iron could act in unity as composite material. This was recognised as an important step towards a more thorough understanding of the material's performance. The tests also proved the fire-resistant qualities of reinforced concrete constructions.

To attract publicity and promote the new technology in the general building world, Wayss provided lectures, press releases, advertisements and eye-catching entries for expositions. Wayss and Koenen published an extensive résumé of the Monier technology in 1887. The Monier brochure contained theoretical reflections on the calculation of reinforced concrete structures, results of Wayss' tests, and a review of actual Monier projects (Disco, 1990). It was a first step towards a more generic understanding of the Monier system, based not only on experience and testing, but also on theoretical exercises. The Monier brochure circulated widely and became an influential book on reinforced concrete construction. It provided guidance to other Monier licensees, supervisors and inspectorates in Germany and elsewhere after it was translated into other languages (Elliot, 1992). The Monier brochure was an aggregation product that influenced many local practices through wide circulation.

Another step towards global knowledge occurred in the network around the very successful 'Hennebique system'. For more than a decade Hennebique performed numerous experiments, developing practical insights in the possibilities of reinforced concrete construction. In 1892 he patented a complete building system, in which columns, beams, joists and floors formed a monolithic whole. This was new, because the earlier Monier system used discrete elements, which were assembled on location. Hennebique established a consulting engineering firm to exploit his patent and set up an international network of licensees. Hennebique's learning strategy was based on intra-organisational circulation and aggregation of experiences. Empirical tests were collected and compared to develop knowledge. But the accumulated knowledge was not backed up by theory or translated into generic statements. Hennebique also organised special training courses for concessionaires and developed a knowledge infrastructure, which included a journal and annual conferences. In 1898 the *Maison Hennebique* started publishing *Le Béton Armé*, a monthly journal that supported his licensees (Elliot, 1992).

The variety of systems increased uncertainty for contractors, customers and inspectorates. It was uncertain how to determine which system was better. Customers had to trust reinforced concrete contractors and their idiosyncratic methods of calculation. Contractors had a 'monopoly of expertise' and their knowledge was largely contextual, geared to specific applications and systems. As long as the innovation race was not decided with the emergence of a dominant design, reinforced concrete producers had no incentive to share their knowledge.

By 1900, thousands of structures, in a wide variety of forms, had been produced (Billington, 1989). Professional groups such as architects, civil engineers, regulators and academics were increasingly challenged to have an opinion about the new construction technology. Another incentive to produce more aggregate knowledge came from increasing interest from large professional customers (Public Works departments, railway companies, the military and inspectorates). These professional customers were demanding and had substantial technological competence. They demanded that uncertainties and risks were reduced before actual construction. Professional engineers, who were employed by large professional customers and inspectorates, favoured a theoretical and mathematical approach. For them, the way to reduce risks

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beforehand was to underpin the technology with data from systematic experiments, which could be used to validate theories and calculations. They demanded a 'rational application' of reinforced concrete, in which calculation could be backed up by theory, and theory could be underpinned by experimental data. This formed an incentive for the production of trans-local knowledge.

In this context, contractors increasingly began to participate in a collective effort to create global, generic knowledge, even though rivals would benefit from increased availability of knowledge. Reinforced concrete was too important to leave only to professional engineers who lacked practical experience. Contractors also disclosed some of their secrets and knowledge to secure interest from professional customers. Some ambitious contractors even published in engineering journals, developing theories and calculations that could be validated.

Contractors and customers also increasingly demanded a legal framework, which they could use in case of conflict (when structures collapsed). Regulations would also enhance legitimacy, signalling to the market that reinforced concrete had become an acceptable technology. Reassurance from an authoritative body would help convince sceptical and hesitant customers. To draw up regulations, generic knowledge was required. Rules could provide credible guidance if standards were based on aggregated knowledge and theoretical insights backed up by experimental findings. This formed another incentive for the shift to the trans-local phase.

Trans-local phase (late 1890s–1910s)

In the 1890s to 1910s, circulation and aggregation activities increased significantly. These activities were targeted at a new goal: the production of knowledge that was generic and applicable *across* locations. This involved roles for new kinds of actors and new kinds of knowledge activities. A division of labour emerged between local and global levels. At the local level, firms and contractors continued to collect hands-on experience, increasingly sharing this with others. But also a global level emerged where professional engineers, professional societies and standardisation committees produced generic knowledge.

At the local level, firms and contractors like Wayss, Coignet and Hennebique began to circulate parts of their knowledge. Ambitious contractors wrote articles on reinforced concrete in journals that were read by potential customers. Some of them gave lectures at meetings of professional societies to convince influential members (e.g. Public Works departments of large cities, Army engineering corps, railway companies). Local actors sometimes tried to aggregate general lessons, but their theoretical background was limited.

Aggregation was more explicitly addressed by intermediary actors such as standardisation committees, professional societies and professional engineers. These actors collected practical experiences from different locations, comparing them to find systematic correlations between variables and establish coefficients for these correlations. This resulted in a collective theoretical-experimental project.

The global-level knowledge activities were supported by an expanding knowledge infrastructure of journals, which provided a forum for theoretical debates about generic knowledge. Early debates took place in *existing* journals on civil engineering and architecture. In 1890, the widely read journal *Wochenschrift des Österreichischen Ingenieur- und Architecten-Vereines* published an article by the Austrian engineer Neumann, in which he criticised the oversimplified assumptions commonly used for calculating the strength of reinforced concrete members. Neumann formulated more realistic substitutes and a set of problems related to the calculability of the strength of reinforced concrete structures in the design stage. Neumann identified the value of the elasticity coefficient of concrete as a key issue. In effect, his article articulated a problem agenda for further research. In 1893, the French journal *La Construction Moderne* began a series of detailed articles on concrete engineering which further specified both problems and promising search heuristics (Elliot, 1992).

In 1895, the Belgian engineer Christophe, who had worked for *Maison Hennebique*, wrote a series of articles on the pros and cons of reinforced concrete, which were published in the Belgian journal *Annales des Travaux Publics de Belgique* and in the French journal *Annales des Ponts et Chaussees* (Elliot, 1992). Christophe presented detailed drawings of reinforcement placements and provided precise descriptions of a large number of projects. He defended and elaborated a simple elastic theory, which had been developed by Coignet and De Tédesco in 1894. In his view, a more sophisticated theory would only add complexity, but not contribute to making constructions more reliable, because of varieties and disturbing influences on local building sites. These publications and debates indicate that a global-level approach emerged, which studied and modelled reinforced concrete generically.

Circulation and aggregation activities expanded, because of demands for a common cognitive and legal framework that could help reduce financial and technological risks. To underpin their regulatory activities, governments needed generic knowledge and they set up standardisation committees, which included civil engineers and reinforced-concrete contractors. Contractors participated in these global-level activities to protect their interests and influence the standardisation process. In France, a State committee tried to establish standardised rules for calculation between 1892 and 1900. Experiments were done at various locations with different contractors, to deduce mechanical laws that would permit reliable calculation of the strength of elements of a given construction. But the high variability between local practices made it impossible to aggregate the various test results. The mechanical properties of concrete depended on the quality of sand and gravel, the kind of cement, the degree of fluidity of the mixture, and the climatic influences during the hardening process.

Meaningful inferences could be made only if this variability was reduced in a laboratory setting. Therefore the global-level knowledge project changed course towards systematic experiments under controlled circumstances. In 1900, the French Minister of Public Works established a new Reinforced Concrete Commission. To establish relevant coefficients and formulas its manager, Considère, created test facilities where systematic and controlled tests could be done using uniform specimens (De Tédesco, 1906). The resulting handbook on reinforced concrete was a substantial contribution to the international theoretical-experimental project. The commission used the findings in 1906 to establish standards, signalling official acceptance of reinforced concrete as reliable and "universal" construction technology in France (Lemoine, 1991). The French regulations were liberal and had a provisional character. Calculations were deliberately simplified because a theoretical technological model was still lacking.

In Germany, the professional engineering society *Verband Deutscher Architecten- und Ingenieur-Vereine* and the newly established *Beton-Verein* took the initiative in 1901 to develop standards for a handbook with rules on design, construction and testing of reinforced concrete constructions. The resulting Extended Concrete Committee proceeded in a rigorous way, working with the elastic theory of structures developed by Mörsch, a key figure in the committee. Testing stations were set up to perform systematic experiments under controlled circumstances. Between 1901 and 1906 the committee generated many experimental data from in-depth studies. The data were used to determine coefficients and parameters and elaborate theories. In 1907 the committee published regulations for reinforced concrete that were less liberal than in France, prescribing only one method of calculation (Lemoine, 1991).

In the same year, the *Internationaler Verband für Materialprüfungen der Technik*, an international organisation for the testing of materials, established an international committee for 'concrete–iron' to review the scientific experiments in different European countries. The committee set out to find answers to questions about behaviour of reinforced concrete under tensile and/or compressive stresses. It aimed to promote the unification of calculations, building regulations and delivery conditions (Rutgers, 1907; 1908). It also standardised algebraic expressions and formulas.

These expanded aggregation and circulation activities were accompanied by the further creation of dedicated intermediary actors. The first technological society for reinforced concrete, the German *Beton-Verein*, was established in 1898, followed by similar associations in France and Austria. In Great Britain, where the introduction of reinforced concrete was slower than in France or Germany, a Concrete Institute was established in 1908. The establishment of technological societies was part of the dynamics in which a local–global division of labour emerged and was institutionalised. The technological societies provided a mechanism for collective action such as collectively funded research and standardisation. They published handbooks and organised meetings, lectures and conferences. Eventually, they began to organise courses and introduced exams that certified skills. In sum, they became carriers of professionalisation of the trade, and aggregation of the technology. Through their work, the field became less fluid. The battle of systems diminished as various systems were increasingly treated as variants of the same building technology.

While early theoretical debates took place in existing journals, the early 20th century saw the creation of new and dedicated journals. The first specialised journal was *Neuere Bauweisen und Bauwerke aus Beton und Eisen* in Germany (1901). In 1905, the journal was transformed into an international specialised journal *Beton und Eisen: Internationales Organ für Armierten Beton*. *Beton und Eisen* became an influential journal in the international field of reinforced concrete. A range of other specialised journals emerged before the First World War in Germany,[2] Switzerland,[3] France,[4] England[5] and the United States.[6] These new journals provided an infrastructure, which facilitated the (international) exchange of knowledge between members of technological communities. Journals provided surveys of technological literatures, book reviews and overviews of developments in theory and practice, and provided a forum for debate and exchanges of opinions. This stimulated integration activities, detailed comparisons and standardisation.

Thus, by 1910, reinforced concrete was no longer a mysterious, local, heterogeneous set of local solutions to specific problems. A local–global division of labour had emerged, supported by existing and new knowledge infrastructures. The result was generic trans-local knowledge, captured in handbooks that compared and evaluated different systems and put forward theories and calculation methods. Technological models were created, which explained performance in terms of a number of salient variables.

At universities the new technology was incorporated in curricula and courses at polytechnics and universities (Lemoine, 1991). Gradually, a new generation of civil engineers was trained how to design and calculate reinforced concrete structures. They subsequently carried the collective knowledge reservoir to the local practices of their employers.

Cosmopolitan phase (1910s–1940)

Reinforced concrete was increasingly applied after the First World War. The recovery of the economy led to many building activities, and it was a period with an open eye for innovations. Post-war optimism and interest in innovation was reflected in the building sector where reinforced concrete was welcomed for new ways of designing and building. Reinforced concrete came to be seen as a modern material, and was used by modernist architects. Reinforced concrete had already gained a good reputation in civil and hydraulic engineering (locks, culverts, viaducts). A combination of factors stimulated its further use in house-building (Schippers, 1995). After the war, traditional building materials were scarce and expensive, making reinforced concrete more attractive. In addition, there was a shortage of skilled labour. Because reinforced concrete promised to save time, construction companies became more interested in the new material. Hence, reinforced concrete was increasingly used in municipal housing projects in Great Britain, Germany and Belgium.

Design and construction with reinforced concrete became a ‘normal practice’, guided by global knowledge. Previously developed standards were widely accepted and provided a legal framework for contractors and customers. Technological societies and branch organisations sponsored ongoing refinements at the global knowledge-level, distributing new insights and findings to local practices.

Also in another way, global knowledge contributed to transforming local practices. Findings, rules and calculation methods from theoretical experiments in controlled circumstances could not be used in local building practices that deviated too much from these circumstances. Therefore, much effort was put into creating more homogeneous local practices, for example, standardisation of raw materials, disciplining and supervision of actual execution of procedures for making reinforced concrete. In other words, local practices had to be made similar to the controlled circumstances under which global knowledge had been produced. Local practices were increasingly adjusted to meet technological rules from the global level, signalling a definitive reversal in their relationship.

Conclusions and policy implications

Each case study is selective, foregrounding some aspects of the empirical complexity and backgrounding others. We could have given more attention to the social and political aspects in standardisation, if we had delved deeper into the working of standardisation committees. But this would not have constituted a new point, since others have done this before (Schmidt and Werle, 1998). The new point of this article was to provide a broad understanding of the dynamics that underlie knowledge flows. In particular we focused on the social and cognitive activities that make knowledge flows possible. In developing a socio-cognitive perspective, the article made important contributions to the debate about global and local levels in technological development. In our view, technological knowledge development proceeds at both levels, with different actors performing different kinds of cognitive activities. Generic, global-level knowledge does not emerge spontaneously from the local level, but is an achievement that requires dedicated socio-cognitive work.

One crucial process is the creation of *social networks and a sense of community*. Such networks are important to facilitate circulation of actors and experiences between local practices. Furthermore, the feeling of being part of a technical community leads to the recognition of shared interests, which is an important incentive for aggregation.

A second crucial process is the emergence of *intermediary actors* that speak for the field. This leads to the creation of a distribution of cognitive labour between local actors (learning on location) and intermediary actors (learning across locations, aggregating general lessons). To make knowledge shareable between locations it has to be decontextualised. This involves not just codification, but also transformation of local knowledge into global-level knowledge. This does not happen spontaneously but requires dedicated global-level *activities*, aimed at creating and maintaining a collective knowledge repertoire. Intermediary actors are important for these activities, working complementarily to actors in local practices.

The third crucial process is the creation of a *knowledge infrastructure* that enables the circulation of experiences and facilitates theoretical debates about generic knowledge (workshops, conferences, journals, courses). The article also positioned these processes and mechanisms in a four-phased pattern, which specified how local knowledge is gradually transformed into global knowledge.

The case study on reinforced concrete illustrated the general perspective and the four phases. Table 1 summarises the case study in terms of the four phases. We conclude that it has a good match with the conceptual perspective, providing a proof of principle and empirical foundation. The case study does not cover the entire empirical complexity of

Table 1. Summary of case study in theoretical terms

Local phase	Inter-local phase	Trans-local phase	Global phase
1850s–1870s; local solutions, trial and error, high variability, trade secrets, 'success without understanding'	1870s–1890s: proprietary systems protected by patents (regional sharing), 'understanding within systems'	late 1890s–1910s: standardisation (building codes and other rules) underpinned by theory and data; emerging knowledge infrastructure of journals and handbooks	1920s–1940s: two-level dynamic, normal practices defined at the global level, collaborative research; courses and training; standardisation of raw materials and disciplining of production process
Driver for transition to inter-local phase: local solutions develop into building technology, new types of customers and markets	Driver for transition to trans-local phase: risk reduction by anticipatory calculation, required by demanding customers, agencies	Driver for transition to global phase: increased interdependencies in reinforced-concrete industry and new social structures	

reinforced concrete. We could have highlighted other, more detailed dynamics (e.g. political struggles in standardisation). But for illustrating the specific processes and mechanisms in our socio-cognitive the case study served its purpose well.

We think that important aspects of our perspective have more general validity than the particular historical case study, in particular local–global dynamics, intermediary actors and knowledge infrastructure. The precise interaction mechanisms may be more complex, however, than in the case of reinforced concrete. Nowadays, new technologies emerge in a context that is pre-structured by previous aggregation processes. The global level will not be empty, but filled with intermediary actors that are 'looking for work'. They will be involved sooner than the third phase (as with reinforced concrete). Furthermore, global cognitive rules will already exist in the early phases, and actors in local practices will build on them when developing novelties. This means that the precise origin of new knowledge is less clear. It is harder to maintain a 'point source dynamic' with dynamics only starting in local practices.

The four-phased pattern, as specified above, came out well in the case study, precisely because the 19th-century world was less 'filled' with global actors and cognitive rules. For 20th-century innovations, complex interactions between local and cosmopolitan levels are likely to be important from the start. So the case study has particularities, which cannot simply be generalised to the 20th century. But the basic concepts are versatile and can be adapted to accommodate 20th-century characteristics of technological innovation.

Our perspective has implications for policies that aim to stimulate the emergence of radically new technologies. These technologies initially have low performance and cannot compete with established technologies on mainstream markets. Hence, they often remain stuck in R&D labs. The literature on strategic niche management (SNM) has emphasised the importance of concrete real-life projects with new technologies (Kemp *et al*, 1998; Hoogma *et al*, 2002; Raven, 2005). These projects form sheltered proto-markets, where users can interact with producers, giving rise to mutual learning and articulation processes. But early SNM contributions made too little distinction between local projects and a global technological niche-level. The latter is carried by an emerging community that shares particular problem agendas, search heuristics, design rules, and ideas about user preferences. These shared cognitive rules

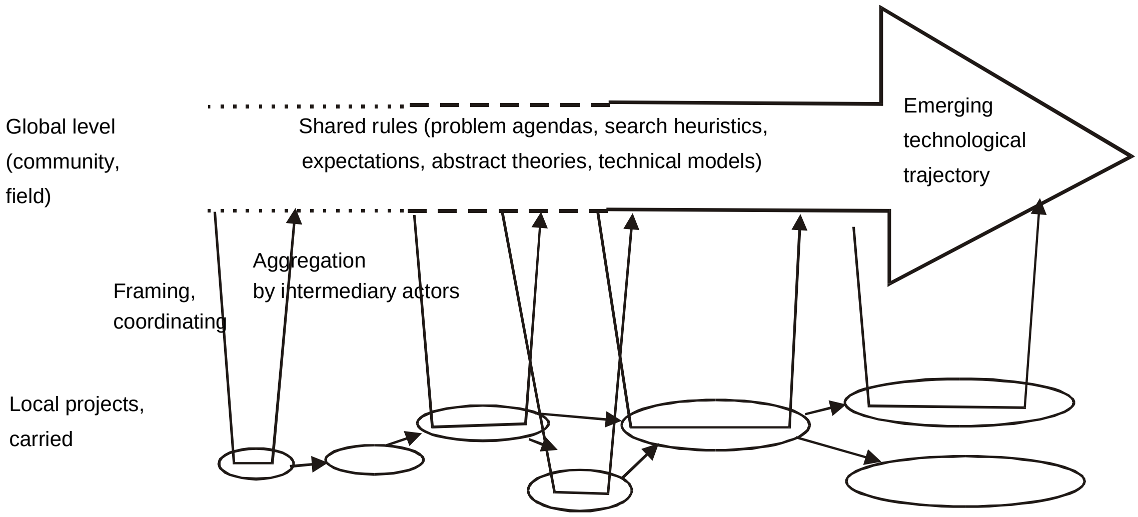

Figure 3. Local projects and emerging technical trajectories

are initially fuzzy and unclear. But sequences of projects can build upon each other, providing space for learning and aggregation processes. A sequence of projects may gradually result in the stabilisation of a global technological trajectory, if experiences from one project are transferred to another project and if general lessons are drawn. Aggregation and intermediary actors are crucial mechanisms for the build-up of such stable rules and knowledge (Figure 3).

Although many experimental projects with new technologies are sponsored by programmes, results too often remain stuck within local projects. More attention should be paid to learning *between* and *across* projects. Knowledge and experiences should not be limited to internal networks involved in local projects, but should circulate more widely and be used as input for the formulation of new projects. Public authorities do stimulate knowledge diffusion (e.g. reports, online databases, workshops), but often in a haphazard way. In our view, knowledge circulation should be taken more seriously. Furthermore, public authorities can do more in stimulating the *aggregation* of knowledge, that is, articulate general lessons and rules from local projects. Notwithstanding difficulties with intellectual property rights, public agencies, which manage R&D support schemes, could do more in the sense of comparing outcomes of different projects, articulating general rules and so on. In other words, they could become more active at a global level, especially in early phases when this level is poorly developed.

Notes

1. Furthermore, the categories of 'tacit' and 'codified' do not map one-on-one with 'local' and 'global'; there can also be codified knowledge in local practices and tacit knowledge at the global level.
2. *Deutsche Bauzeitung: Mitteilungen über Zement, Beton und Eisenbetonbau* and the *Armierter Beton: Monatsschrift für Theorie und Praxis des Gesamten Betonbaues*.
3. *Revue de la construction moderne en béton et béton-armé* and *Il cemento*.
4. *Le fer-béton (système Matrai).*
5. *Concrete and constructional engineering* and the *Ferro-Concrete*.
6. *Concrete*, the *Cement and Engineering News*, the *Cement*, and *The Cement Era.*
7. Hoogma *et al* (2002) studied local experimental projects with: fleets of battery-electric vehicles in La Rochelle (France) and Rügen Island (Germany); small lightweight electric vehicles in Mendriso (Switzerland); experiments with car sharing (Switzerland); and individualised public transport in Praxitèle (France).

References

Bijker, W E 1995. *Of Bicycles, Bakelites and Bulbs: Towards a Theory of Sociotechnical Change*. Cambridge, MA and London, England: MIT Press.

Billington, David P 1989. *Robert Maillart and the Art of Reinforced Concrete*. New York: MIT Press.

Colby, A L 1909. *Reinforced Concrete in Europe*. South Bethlehem, Penn.

Cowan, R and D Foray 1997. The economics of codification and the diffusion of knowledge. *Industrial and Corporate Change*, **6**(3), 595–622.

Cusack, Patricia 1987. Agents of change: Hennebique, Mouchel and ferro-concrete in Britain, 1897–1908. *Construction History*, **3**, 61–74.

De Tédesco, N 1906. The historical evolution of reinforced concrete in Europe. *Concrete and Constructional Engineering*, **1**, 159–170.

Deuten, J J 2003. *Cosmopolitanising Technology: A Study of Four Emerging Technological Regimes*, PhD thesis. Enschede: Twente University Press.

Deuten, J J and Rip, A 2005. Making technologies cosmopolitan: the role of epistemic aspects in the dynamics of technology. To be submitted to *Research Policy*.

Disco, N 1990. *Made in Delft: Professional Engineering in the Netherlands, 1880–1940*, PhD thesis. Amsterdam: University of Amsterdam.

Elliot, C D 1992. *Technics and Architecture: The Development of Materials and Systems for Buildings*. Cambridge, MA: MIT Press.

Hård, M 1994. Technology as practice: local and global closure processes in diesel-engine design. *Social Studies of Science*, **24**, 549–585.

Hoogma, R, R Kemp, J Schot and B Truffer 2002. *Experimenting for Sustainable Transport: The Approach of Strategic Niche Management*. London and New York: Spon Press.

Kemp, R, J Schot and R Hoogma 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. *Technology Analysis and Strategic Management*, **10**, 175–196.

Latour, B 1999. *Pandora's Hope: Essays on the Reality of Science Studies*. Cambridge, MA: Harvard University Press.

Latour, B and S Woolgar 1979. *Laboratory Life: The Social Construction of Scientific Facts*. London and Beverly Hills, CA: Sage.

Lemoine, Bertrand 1991. Fer et beton en France (1850–1920). *History and Technology*, **7**(3–4), 267–278.

Nelson, R R and S G Winter 1982. *An Evolutionary Theory of Economic Change*. Cambridge, MA: Bellknap Press.

Raven, R P J M 2005. *Strategic Niche Management for Biomass*, PhD thesis. Eindhoven University, The Netherlands

Rip, A 1997. A cognitive approach to the relevance of science. *Social Science Information*, **36**(4), 615–640.

Rouse, J 1987. *Knowledge and Power: Toward a Political Philosophy of Science*. Ithaca, NY: Cornell University Press.

Rutgers, S J 1907. Internationale commissie voor beton-ijzer. *De Ingenieur*, **22**(34), 641.

Rutgers, S J 1908. Rapport betreffende ongevallen met beton-ijzer constructies in Nederland. *De Ingenieur*, **23**(5), 71–74.

Schippers, Hans 1995. *Bouwt in beton!: Introductie en acceptatie van het gewapend beton in Nederland (1890–1940)*. Gouda: Betonvereniging.

Schmidt, S and R Werle 1998. *Coordinating Technology: Studies in the International Standardization of Telecommunications*. Cambridge MA: MIT Press.

Turnbull, D 1993. The ad hoc collective work of building gothic cathedrals with templates, string and geometry. *Science, Technology and Human Values*, **18**, 315–340.