3.10
ENABLING CIRCULAR ECONOMY IN THE AEC INDUSTRY THROUGH DIGITALIZATION

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Introduction

On the one hand, some may argue that while "a powerful tool for cracking problems and leveraging opportunities", design is "extremely wasteful and destructive" due to its "ephemeral nature, fueled by the ceaseless consumer hunt for change, novelty and innovation" (Chapman, 2017: 161). If this statement is assumed true, it can be argued that it is even more so in the Architecture, Engineering and Construction (AEC) industry. Nonetheless, the human-centered design,[1] as opposed to user-centered or user-friendly design, has been promoted more and more recently. On the other hand, there exists the question of "Can sustainable design (in architecture) drive change?", a moderated version of the more radical query "Is sustainable architecture a style?"; one of an existentialist nature which has been looming in quest for a new style in architecture. Pleading for a new style to anchor to, happened to look like the 'swan song' for many while the mainstream movement in architecture tended to swerve gradually towards anonymity of/in style liberating itself from the rubberstamp of time due to many reasons, the least of which being the unprecedented fast pace of change literally in anything and everything. This latest plea for immortality—that is to be able to live long beyond the apprehensible time, although not unprecedented in the history of architecture when we look, for instance, at necropolises across the ancient world, has had a totally and utterly different driver behind it in our times. Moreover, the immortality as the humankind's longest standing obsession as evidenced in the earliest non-religious tale in the history—Epic of Gilgamesh—is intertwined with anthropocentricism beyond its traceable roots dating back to the Renaissance with Civic Humanism—as coined by Hans Baron. As the humankind has not yet successfully managed to overcome the mortality associated with themselves to satisfy their anthropocentric aspirations, the yearning hope to do so ensued—along many other retorts—and incarnated in their anthropospheric[2] interventions in the status quo of their natural environment. Tony Fry tells us that as we create, we also destroy, and that 'sustainment' is imperative to counter the inherent 'defuturing'—which he defines as the agency of unsustainability in the medium of time—of the economy, cultures and institutions of the contemporary 'developed' world (Fry, 2003). In architecture and the city, however, the anthropocentricism has had another turn from the very beginning. This early divergence grew from the early ages, alongside the evolution and development of human-centricity in both political philosophy and historiographical constructs. The anthroposphere, as architecture, city, the built environment, and the human habitat in a broader sense are, has inherently had enough

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gravitas—weight, traction—which, when conjoined with its *pietas*—not only as regard for discipline but also as a means to materialize it—and its *severitas*—strictness in the sense of rigor and longevity as opposed to rigidity—has enabled it to foster reallocation of the center of gravity, focus and attention in human-centered constructs and movements in architecture from the human beings to the anthroposphere itself rather as a demarcating if not a circumscribing artifact and at its best, at the service of the humankind. Alongside other benefits it has to offer, circular economy and the thought process associated with it, which involve keeping the resources and products in use for as long as possible, can contribute to finding some answers to such quest in our anthroposphere; this time with a different worldview promising a prospect of sustainment.

From digitization to digitalization and beyond

Thanks to cheap labor, and even cheaper time in less-developed construction economies of the Global South, the construction materials have systematically been salvaged, classified, and stockpiled on demolition sites to be then used in the new buildings on the same or a proximate site. One of the justifications provided for applying such processes—in addition to cost saving—has been the rhetoric of 'old is gold', implying that old materials contain and hold better quality and stand the test of time more effectively. There have hardly been regards for the environment *per se* and the radii of such circularities hardly passed the boundaries of a single construction project site, hence this can best be regarded as a closed quasi-circularity. A fully fledged circular economy requires a set of prerequisites including a technological infrastructure to be able to flourish successfully.

Some of the first traces of digitization—and of early automation,[3] one can argue—dates back to as early as early 1800 with punched cards in Jacquard machines,[4] where there was no onerous reliance on advanced technologies. Expanding on the concepts associated with the Greek word *technē* at its origins,[5] technosphere,[6] provides the opportunity to expand the discourse onto technological underpinnings required to facilitate circular economy. Gartner's IT Glossary[7] characterizes digitization as changing from an analog to a digital form, without any different-in-kind alteration to the initial process itself. In this sense digitization does not necessarily need to carry special characteristics or qualities with reference to its underpinning technological infrastructure. Despite digitization, digitalization takes much more and just to start with, is "fraught with ambiguity and confusion" as Bloomberg suggests in his article for *Forbes*.[8] Although both digitization and digitalization belong in technosphere and therefore are in the same category with architecture as a part of anthroposphere (Figure 3.10.1) and are sometimes used interchangeably, they are fundamentally different in their significance as well as their implication. While digitization is about data, digitalization is concerned with information. Transformation beyond digitalization—also labeled as 'digital transformation'—involves, in addition to data and information, knowledge at organizational level. While the scope of digitization does not go beyond the technosphere, digitalization finds its conviction in association with its impacts on social systems (Figure 3.10.1), whereas digital transformation's significance and implication span over technosphere—to both Earth and Social Sciences. Therefore, digital transformation is more likely to be able to provide architecture—both as a social system and a part of the traditional technosphere—with more meaningful channels to convene the 'Dialect of Sustainment' with Earth systems. One of such channels is circular economy.

De-learning the learned to (re-)learn novelties

The pandemic which was triggered in 2019 has caused substantial changes in almost everything. It caught us, our societies, culture, education, businesses and economies, industries, production, and manufacturing, even politics by surprise and faced us with challenges which we all hope to turn out to be Dolos's forged footless Veritas. Nevertheless, those challenges, if not unprecedented, were

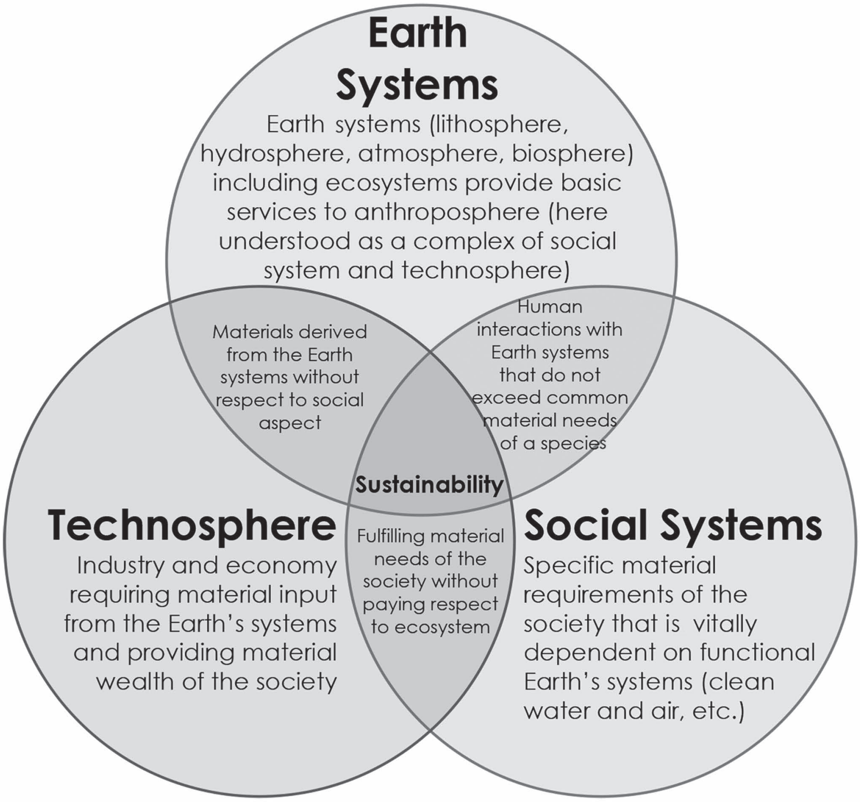

Figure 3.10.1 Relationship between Earth systems and anthroposphere.

Source: Přikryl et al. (2016).

unanticipated. To mark this pandemic as a turning point with some implications for our argument no matter how major or minor we tend to assume them, we would call it 'Event-19', or 'E-19' in short. E-19 forced us to familiarize ourselves more with "startup culture"; to become more goal-oriented with more flexible, adaptable plan(s) and if possible few contingency plans at any particular point in time. It also pushed many of us, collectively or individually, not only to learn new things and sometimes unlearn some of what we had taken religiously for granted—almost as axioms, but also to expect the unexpected and moreover to learn how to become fast learners. For that, Meyer and Land's 'threshold concepts' (2003) had to be passed and relatively in a short span of time. One of the barriers to 'threshold concept' in learning, is involvement of some forms of 'troublesome knowledge', which Perkins (1999) defines as what appears counter-intuitive, alien (emanating from another culture or discourse), or seemingly incoherent. The mastery of a threshold concept can be impeded due to prevalence of a commonsense or intuitive understanding of it and reversing this intuitive understanding is also troublesome because it can involve an uncomfortable, emotional repositioning (Cousin, 2006). E-19 also helped us overcome some of those uncomfortable and emotional challenges alongside some of our cognitive barriers to information seeking (Savolainen, 2015). Overcoming those social, emotional, and cognitive barriers, although it might look like less tangible achievements, serves as a keystone for circularity to succeed in the construction economy to the extent which had not been explored prior to E-19.

The circularity

The shift from product to service in the economy is a longstanding and venerable concept, where being in possession of technological goods and products is reversed into renting them for the service they provide, as a functional unit in a 'performance economy' or a 'functional service economy'. Together with those, the concept of 'Economy in Loops' dates back to 1970s when Stahel and Reday-Mulvey argued, in a report[9] to the EU Commission, that there is potential for substituting manpower for energy. Benyus's Biomimicry,[10] Lyle's Regenerative Design,[11] Pauli's Blue Economy,[12] McDonough and Braungart's Cradle to Cradle,[13] and Industrial Ecology[14] are just to name but a few concepts with which circular economy shares some principles or from which it borrows some fundamental inspirations or concepts. Plugging into Braungart and McDonough's Cradle to Cradle's material cycles, the Ellen MacArthur Foundation (EMF) proposes biological and technical material flows in their 'Butterfly Diagram' to then tell us that with current advances, digital technology has the power to support the transition to a circular economy by radically increasing virtualization, dematerialization, transparency, and feedback-driven intelligence.

Along with epistemological and ontological impacts that E-19 has had and will continue to have on the ways in which we live, work, and play, it put the capacities, possibilities, and efficiency of technologies associated with the virtual environments into a rigorous test. It also highlighted the necessities and bolded out the requirements associated with this transition process from actual to virtual. Digital technologies—both hard and soft—have been utilized at mass scales to facilitate virtual environments for activities which were run in physical settings and environments pre-E-19. Some of the lessons learned during E-19 can well be carried over to post-E-19 to continue enabling circularity in the construction economy and this promises bright futures for circular economy in the AEC industry.

The circularity in and out of the construction economy

The construction industry has been blamed for being ineffective, adversarial, fragmented, and incapable of delivering for its customers for over 80 years.[15] Its fragmented nature makes it inherently different from manufacturing and service industries, hence facing it with different challenges in industrialization of the production process, its market size, diversity of customers' needs, wants, requirements, and preferences, and leveraging economies of scale for personalized end-products (Farr et al., 2014; Goulding and Arif, 2013). The inbuilt environmental destruction at either end of the linear production-consumption system (Chapman, 2017) in the construction industry is therefore different from those associated with activities in manufacturing and service industries. A performance economy or functional service economy requires new reinterpretation and novel mechanisms tailored to the specifics of the construction economy if they are to be successfully applied in architecture, the built environment, and construction. In construction, an industry-wide call for fair and transparent risk allocation has driven several alternative delivery methods such as DBO (Design-Build-Operate) and DBOT (Design-Build-Operate-Transfer) in PPP (Public Private Partnership) long-term contracts with PFI (Private Finance Initiative) procurement method at their core. Selling the service—instead of goods or products—is envisioned in such alternative long-term contract types rather as a subsidiary intention or a byproduct. However, those methods have not been very effective in changing the business model from a linear to a circular economy model. Besides, even if this supposedly worked for public projects, the private projects—which shape a significant portion of the construction market economy—are less likely to benefit from what those alternative delivery methods may have had to offer.

E-19 will change the supply-demand flow and balance for space. The pace and extent of demand for development has started to shift due to E-19. It has also redefined the rules and principles of creation of space. Norms, standards, and legal and legislative requirements for minimum Gross Floor Area (GFA) are expected to rise significantly to be able to accommodate safer and more hygienic work, retail, and recreation spaces. The nature and character of needs and requirements for the built environment have also witnessed a major change. As a result, demand for new building types such as 'Resimercial' is starting to emerge in the construction market. E-19 will have some impacts on non-architectural tectonics of buildings; more specifically on structures and building services. The needs for spaces with improved cleanability will have consequences on spaces sizes, accessibility, probably more HVAC services to provide improved air exchange and UV-light sanitization systems for space and furniture. The impacts on energy consumption and GHG emissions of buildings due to new legislative focus on increased fresh air, improved filtration, higher air exchange rates, and UV-light cleaning systems would make buildings less likely to be able to achieve the ambitious set targets for cutting back on their environmental impacts. The rising intentions to use so-called 'anti-viral materials' such as copper and silver will increase the environmental footprint of buildings radically. The previous need for production (production of space included) will not be the same as what it was pre-E-19. We get domesticized and acquainted more with what we have had at our disposal post-E-19—be it a phenomenological illusion or a cognitive error (Miller et al., 2020)—and therefore, adapt and adjust to our changing environment to find better, cleverer, and more durable, long-lasting ways to cope with the change, resuming utilizing and adapting the properties, goods, and spaces we have, if we are to survive, as Megginson's quote of Darwin's *Origin of Species* avers. And that is why this is a unique opportunity for a circular economy equipped with and enabled through an unprecedentedly developed, advanced IT to become more prevalent not as a remote, hypothetical, idealistic agenda but as a practical, workable, and obvious alternative to our unsustainable insights towards, approaches to, and practices in our day-to-day living and our preferred lifestyle pre-E-19.

There have been recent attempts to explore the potential for—and in very limited cases applicability of—circular economy in the AEC industry. Those attempts so far have hardly accounted for the inherent mismatch between the construction industry and other industries, and therefore aimed to promote circularity in the construction economy the exact same way it has been operationalized in other economies. In such efforts, the necessity of change in the prevailing business model in the construction industry has been neglected, not to mention concerted efforts, and a unified will to succumb to such change. This is a change associated with the social systems and constructs of the anthroposphere, which is by far more difficult to achieve. At the risk of a major failure, this may or may not be worth trialing. Alternatively, a 'domesticated circular economy', where the specifics of the construction industry are taken into account, as less enlivened as it may look, may have a bigger momentum to last the test of time and therefore, a higher change to succeed.

The future of circular economy in architecture, the built environment, and construction

The circular economy is a closed-system (Pearce and Turner, 1990) with a circular supply chain which accounts for extraction and yield of resources, waste reduction, assimilating and recycling capacities (Batista et al., 2018, De Angelis et al., 2018). A closed loop supply chain works well in circular manufacturing due to economies of scale (number and variation of extant products or goods), standardization (of the product and process), and modularization (including product platform design, interface design, component-sharing and component-swapping, dimensional and tolerance coordination). Some 15 million famous Model Ts were built by Ford in just under 20 years between 1908 and 1927. Aston Martin V8 sold only 4021 cars in somewhat a similar period between 1969 and 1989. While the former as a classic example of mass production 'statistically' qualifies for a circular economy model, being known as an individually personalized product at the far end of the mass production-personalization spectrum, the latter has its appeals for high-end approaches in the circular economy, for example refurbishment (restoration) and remanufacturing. Unlike manufacturing products, buildings do not usually get to enjoy the benefits and advantages that 'economies of scale', at one end, or the 'collectibles' appeal', at the other, may have to offer. In the construction industry, the final product of one particular supplier—for instance, a housing developer—is similar enough to one of any others to share construction processes as well as building elements and components yet not distinctive enough to be exclusively limited to the initial supplier for repair and maintenance, reuse, recycling, upcycling, refurbishment, or remanufacturing. On the other hand, each building is unique enough to form an exclusive repository of materials and components—acting as a single bank account in a materials bank[16] yet not similar enough to other products to be rolled out as one prototypical product. And this is yet another reason why the concept of circularity should evolve to accommodate the specifics of the AEC industry; what would be different from what circularity entails in manufacturing industries.

The raising awareness campaign about how unsustainable, resource-intensive, and wasteful the linear production-consumption linear spectrum in the AEC industry is, has started paying off. More than ever before, we, as architects, designers, engineers, contractors, and facility managers, think twice about short-, medium-, and long-term consequences of our decisions before putting a pen on the paper, manipulating a BIM model, starting excavation on a construction site, or writing the facilities and assets maintenance strategy reports.

Previous research has highlighted "ample room for growth in building material circularity business models", "holistic approach as a key", "public procurement as a powerful driver" and need for "regulatory [re]consideration" (Wang et al., 2017: 317), "Material Passports"[17] for optimizing value recovery from materials (Luscuere, 2016), and a systemic view to help with comprehensive assessment of reuse potential of building elements (Durmisevic et al., 2017), where—among many others—a centralized management system for building and material information (Debacker et al., 2017: 116) seems to be a shared key principle. This is inspired by lessons learned and experiences transferred directly from the circular economy as practiced in manufacturing industries.

It should, however, be noted that most of the current research on or around circular economy in the AEC does not take into consideration any significant shift from conventional materials to advanced, alternative, or high-end materials. Such materials can be argued to have been more prevalent in the manufacturing industries but traditionally enjoyed a low uptake in the AEC industry. Moreover, the built environment has a relatively low renewal rate. It is estimated that in many developed construction economies up to 80% of building stock in 2050 is already in existence and that many buildings which would have come to the end of their service life would be over 50 years of age.[18] As a major repository of materials, such buildings are carrying the mainstream construction materials and technologies of their era of conception hence are highly unlikely to contain non-conventional technologies or radically innovative materials. On the other hand, the way in which conventional organic, natural, and synthetic materials are being used, and hence, as a consequence of potential application of circularity, salvaged, retrieved, recycled, or upcycled is highly unlikely to change. Therefore, the main scope and signification of the circular economy is expected to remain chiefly concerned with the existing material repository of the buildings with a high average age range. However, new, emerging, alternative, and innovative materials such as shape-memory materials—which date back to 1930s—nano- and bio-materials gradually make their way from high-tech engineering disciplines and manufacturing fields through to the AEC industry. If this happens, and depending on its pace, spread, and extent, such materials will potentially have some unprecedented impacts on how the concept of circularity in the AEC will evolve in the future. Circular economy which might appear to be a painstaking process due to its inherent nature, and processes associated with extraction, production, maintenance, and retrieval of materials, might become either an easy daily practice or a more demanding, complicated, and specialized process. While the possibilities at each end of the spectrum are countless, the exact dimension, depth, and breath of such possibilities remain to be explored more closely and then built upon once a few case examples are focused on and studied with enough depth.

With quantum computing, TPUs, AI (and ML/DL) models for edge computing, the technological hurdles in the technosphere had been overcome beyond what is required to facilitate a 'domesticated circularity' in the construction economy even before E-19 all started. However, the circularity in the construction economy is still in need of one last missing link that is a systemic transformation into a discipline-specific approach, what we would call a *spherical economy*. A systemic technology-enabled transformation in circularity allows for accommodating or compensating for the fragmentation inherent in the construction industry. Local information points will work as data gathering agents to document data pertaining to design, extraction, production, manufacturing and fabrication processes, transport, construction and assembly, use and maintenance, and end-of-lifecycle scenarios for individual buildings or civil and infrastructure projects. All collected data can be stored locally in a Building Information Model which is locally centralized to all data and information associated with that specific building or project. Up until this point, this envisaged future shares its vision, principles, and ambitions with what has been advocated by previous research for future uptake of circular economy in the construction industry; that is a closed-loop economy enabled by a centralized management system for building and material information with building as material banks where the materials obtain 'identity' owing to their 'passports'. This said, it should not be forgotten that the very premise underlying this advocacy is that the buildings by default are similar if not identical to manufacturing products. While supposing this premise in essence might look harmless, even necessary to start with, its detriments might derail the concept of circularity in the construction industry or wear out the enthusiasm or the conviction for migrating to or even moving towards circularity.

From BIM to circularity in architecture, the built environment, and construction

UK Government's BIM Mandate of 2012 was probably the first concerted initiative in the world to boost what seemed to be the remedy to many perceived deficiencies and flaws in the AEC industry nationally. It was predicted that it would roll out to other construction economies around the world and help enhance the performance in the sector. It worked with some countries who followed the same path but was not as effective as it was hoped to be with others. One first reason was that some construction economies (and even some sectors of the construction industry in the UK) were not quite up to speed with technology or willing to embrace the cultural change it would have required. On the other hand, there were some construction economies (e.g., Germany) where there was not much BIM could offer that did not already exist. Nonetheless, the Pandora Box had already opened and there was no other alternative but to admit that while there were (and will always be) some players who are slower, more suspicious, or more reluctant to catch up or pick up in time, 'the change' had already been triggered and could have not been undone or reversed. 'The change' was an industry-wide appreciation for Kaizen[19] almost unanimously all around the world. Although not unprecedented, what was different this time round was that it was showing some prospects for 'sustainment', due to the level of technology affordably available at a large and all-inclusive scale. It took a while, but this raised the collective concern that BIM was just the start point and not the ultimate goal to aspire to and that a construction-specific digital transformation would be needed if the continuous improvement was to be adhered to and delivered. This does not revoke what Eastman (2011) tells us about what BIM has to offer not only as a tool, and technology, but above all as an environment, together with its endless capabilities and benefits. In an internal research report in the University of Brighton in 2020 we mapped circular economy in the construction industry against several BIM models of University building assets and showed that, in theory, all the elements and requisites that a fully functional circular construction may need in its classical sense, are either by default embedded in or achievable through BIM Level 2.[20] There are even proprietary plug-ins which can perform LCA of a building model in several BIM applications, to enable and consolidate circular economy more quantitatively. To this end, data and information technology are already available, functional, and fully capable of enabling circularity in the construction economy, yet a 'digital transformation' that involves knowledge at an organizational level, is still required if *spherical economy* is to be successfully operationalized.

Beyond circularity in the construction economy

We are standing at a turning point where all the preliminaries to shape a true *spherical construction economy* are in place. To achieve this, circular economy needs to move from a 2D static, flat, passive interaction mechanism to a 3D dynamic, real-time (or JIT: Just-In-Time), active exchange mechanism thereby metamorphosing from a circle into a *sphere* in which the circularity works multilaterally in different dimensions and around different axes. At its core, a *spherical economy* requires a coordinated information network—centralized locally yet interconnected regionally and nationally—to nurture dialogue between different buildings, each of which acting traditionally as a 'material bank' in the existing models. The *spherical construction economy* will move the concept of circularity forward, where each building—as a material bank—acts at a multidimensional and multidirectional level as an individual building account in the 'building banks' in each region. The building banks of different regions are all linked through a unified integrated system coordinated through and synched via a national Building Account Routing Number (n-BARN). Once the local and national databases are set up and linked up, the n-BARN databases of different countries can be interconnected through an international Building Account Routing Number (i-BARN), albeit rare, but if and when absolutely necessary, facilitating the exchange of specialized materials beyond the limits of the country of their origin (Figure 3.10.2).

As a start point, a BIM model will be created centrally where all the data and information pertaining to materials as well as their associated construction methods and sequences are stored at the pre-construction stage. This will serve as the first locally centralized data point in an IoT-enabled information grid. A live update process will be checked and verified using AI expert systems on a random or all-inclusive basis. This is where the concept of 'material passports' comes into play, through which the material nexus through their associated logs of data is traceable back to its source at any point in time over the lifecycle of the building up to the specific time of data interrogation with potential pathways the materials may be able to take beyond that point in time. It is important to ensure that this traceability is always maintained like a forensic 'chain of evidence' to be able to use data in feed-forwards into the potential circular cycles that each material can possibly take in the future. To facilitate this, during the construction phase, a live register of materials will be recorded using vetted technologies such as RFIDs and fed back into the model through the designated IoT network. This keeps updating the BIM model's material repository on a live, real-time basis to ensure all the design and specifications data are updated in the pre-construction BIM model to help create an as-built BIM model forming the asset's 'Digital Twin'.[21]

The Digital Twin forms the local meta-source for a 'building account' in a centralized location native to each building and is kept up to date by the construction management team (during the construction phase) and facilities management team (during the operational phase) for a single building, asset, or an entire estate depending on the size of the project or the organization the building or buildings belong to. The live feeds from 'building accounts' will be forwarded regularly to a regional 'building bank' and are kept securely. All these individual 'building accounts' deposited in regional 'building banks' throughout the country are linked to a central 'national building bank' in which each building is ID'd using their unique n-BARN. Throughout the service life of the building the records in each 'building account' gets updated automatically and in real time. This will

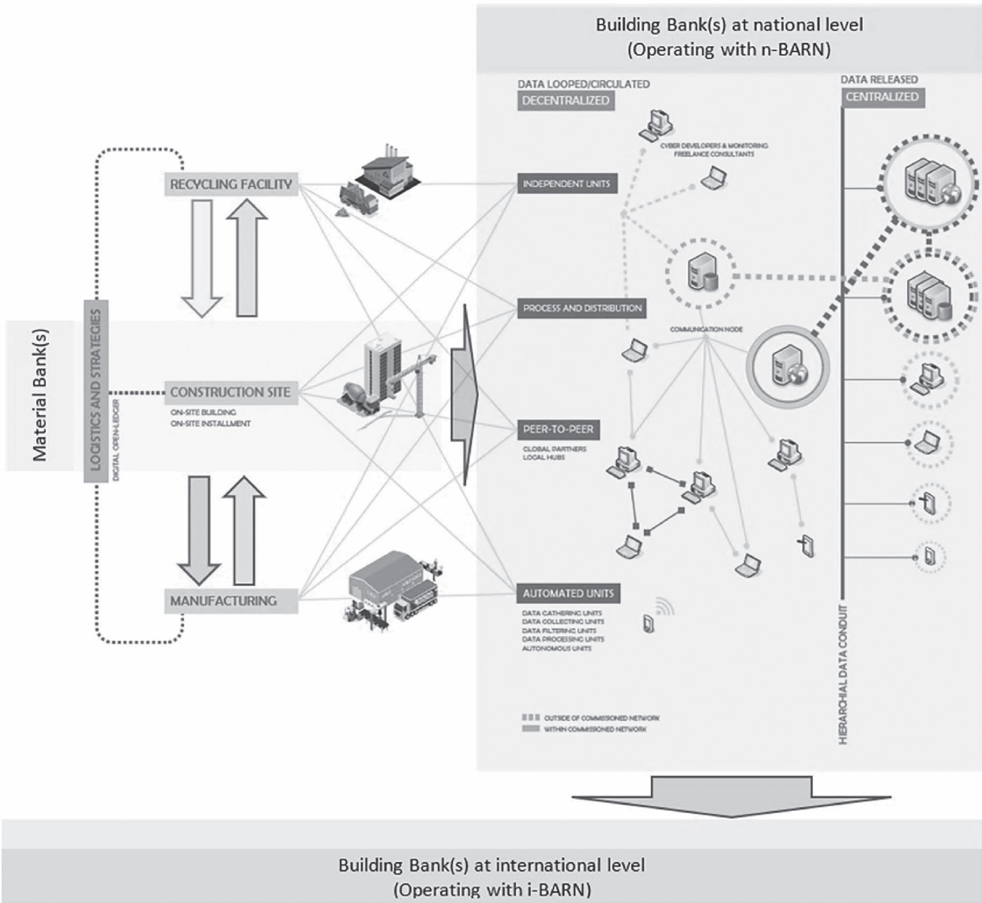

Figure 3.10.2 Left: The flow of raw/used materials between building as a material, manufacturing, and recycling facilities.

Middle: Flow and exchange of data pertaining to individual material banks to and from Building Banks at the national level; decentralized units help collect looped and circulated data through independent units, process and distribution networks, peer-to-peer feedback and update loops and automated units or systems.

Right: Data is centralized, clustered, tagged, and made available (released) to the potential subscriber-user in new and refurbishment or restoration projects on a priority basis.

Bottom: The data will also be linked to the central building bank at the international level.

automatically get fed forward to regional building banks and through them to the national building bank. Using the *spherical* model in construction economy, the lifecycle schedules of all buildings are kept in a central database in the regional and national building banks which can be accessed by registered professionals or vetted tradespersons in the AEC industry. This way, if and when a building is about to go under major refurbishment or comes to the end of its service life and is scheduled to be demolished or decommissioned, it can benefit from surplus and salvaged materials from, or offer its materials to, other projects in the region and throughout the country on a priority basis. Taking into account the history, its served life, its remaining life, its associated, offset, and left-over impacts as well as the impacts associated with the procurement process including transportation, a built-in 'impact calculator' will be used to calculated all environmental impact categories associated with the procurement and transportation of the material or materials associated with or needed in the building. This will help find the most optimized solution for circularly efficient options for the project or projects—new or refurbishment—where there is a need for those materials. Using the n-BARN network, a 'wish list' or a 'waiting list' can be created. This will help find resources in case an unplanned emergency upgrade was deemed necessary in any of the buildings in the system, which may release their inventory of material to the market sooner than initially planned.

The future of sphericality in the construction economy

Sphericality in the building and construction economy has an infinite future to unfold to. While it starts as *spherical economy*, once the domesticated circular economy gets fully operationalized in the AEC industry, it can start reshaping the business model in the industry in its entirety. Eventually, *spherical economy* will mature to the extent from which yet another systemic level of circularity will bloom. While materials still play the key role, the center of focus in this new business model will shift towards the *sphericality of space*, where space serves as a functional unit in a 'performance economy' in the AEC industry. At this level, *spherical space*, which only complements the matured levels of *spherical economy*, is where the space as a product or asset will be shared, recycled, upcycled, reshaped, reformed, and re-engineered or refurbished (remanufactured) in part or in its entirety at a multidimensional and multidirectional level to extend its service life beyond the lifecycle of its constituent materials and components, working together in association with other *spherical spaces*, extending the overall lifespan of the building assets they belong to.

Notes

1. See for instance "The Seven Tenets of Human-Centred Design" as articulated by the Design Council, UK, available at: www.designcouncil.org.uk/news-opinion/seven-tenets-human-centred-design.
2. The term anthroposphere was used to indicated human-generated structures and systems or the human-generated equivalent of biosphere. Both terms were first coined by Austrian geologist Eduard Suess in C19th.
3. Also the Jaquet-Droz family's automata, circa 1770s, which are believed to be the first robots ever built.
4. Developed after earlier inventions by Bouchon, Falcon, and Vaucanson between 1723 and 1741.
5. The word *technē* in Greek refers to an art or a craft (bridging the new modern gap between arts and crafts) with an emphasis on practical rationality (and to some extents practical wisdom). The materiality, concreteness, and context-dependency of *technē*, as originally intended, is not what is necessarily imbued with modern or contemporary use of the term 'technology', what entails a semantic transformation of the term in conjunction with its lexical transfiguration.
6. 'Technosphere' coined and defined by Peter Haff as "a global apparatus that searches for, extracts, and does work with (mostly) fossil energy" is sometimes used loosely as an equivalent to anthroposphere, while more accurate readings of x-spheres suggest that it is only together with social systems that technosphere forms anthroposphere. For more on technosphere see HAFF, P. 2014. Humans and technology in the anthropocene: Six rules. *The Anthropocene Review*, 1, 126–136.
7. See www.gartner.com/en/information-technology/glossary/digitization.
8. See www.forbes.com/sites/jasonbloomberg/2018/04/29/digitization-digitalization-and-digital-transformation-confuse-them-at-your-peril/?sh=2970a2a12f2c.
9. Stahel, W. R. & Reday-Mulvey, G. 1977. *The Potential for Substituting Manpower for Energy: Final Report for the Commission of European Communities*. Geneva: Battelle Geneva Research Centre.
10. See https://biomimicry.org/.
11. See https://env.cpp.edu/rs/rs.
12. Based on 21 founding principles, the Blue Economy advocates solutions which are governed by their local environment, and physical and ecological characteristics, putting the emphasis on gravity as the primary source of energy. See www.gunterpauli.com/the-blue-economy.html and also: www.theblueeconomy.org/.
13. Coined by Stahel but developed and quantified by McDonough and Braungart. For some more details see www.c2ccertified.org/.

14. Commonly associated with the paper Gallopoulos, N. E. & Frosch, R. A. 1989. Strategies for Manufacturing. *Scientific American*, 261, 144–152, but with roots dating back to C19th. See also Kapur, A. & Graedel, T. E. 2004. Industrial ecology. *In:* Cleveland, C. J. (ed.), *Encyclopedia of Energy*. New York: Elsevier.
15. Reaching for the Skies (1934), The Simon Report (1944), The Banwell Report (1967), The Emmerson Report (1962), The Latham Report (1994), The Egan Report (1998), Rethinking Construction (2002), Never Waste A Good Crisis (2009), The Government Construction Strategy (2011), The Farmer Review of the UK Construction Labour Model (2016) are to name but a few reports highlighting the construction industry's inefficiency, ineffectiveness, lack of productivity, and low GVA.
16. The idea of a material bank was elucidated in 2014 in the Resource Abundance by Design presentation by William McDonough at the World Economic Forum in Tianjin, China (see www.youtube.com/watch?v=OcO1O99UoUs&feature=emb_logo), the core concept of an EU Horizon 2020: Buildings as Material Banks (BAMB) which was kick-started in September 2015 (see www.bamb2020.eu/), in which the British Research Establishment (BRE) has been one of 16 partners (see www.bretrust.org.uk/news/bamb-building-as-material-banks/) to provide significant resources in research to develop new ideas and ways of embedding circular economy thinking into the built environment.
17. The concept was initially used in 'Towards the Circular Economy: Accelerating the Scale-Up across Global Supply Chains' report to the 2014 World Economic Forum, available online at: http://www3.weforum.org/docs/WEF_ENV_TowardsCircularEconomy_Report_2014.pdf. Also see www.bamb2020.eu/topics/materials-passports/; www.bamb2020.eu/topics/materials-passports/what/; and 'Materials Passports—Best Practice' report available online at: www.bamb2020.eu/wp-content/uploads/2019/02/BAMB_MaterialsPassports_BestPractice.pdf.
18. Assuming that they do not qualify as cultural heritage or considered to have architectural values or merit to the extent that makes them worth saving.
19. "KAIZEN means improvement. Moreover, it means continuing improvement in personal life, home life, social life, and working life. When applied to the workplace KAIZEN means continuing improvement involving everyone—managers and workers alike." Masaaki Imai, Founder of Kaizen Institute. See www.kaizen.com/.
20. For BIM Maturity Levels see BS 7000–4:2013, and PAS 1192–2 (now replaced with BS EN ISO 19650).
21. The term 'Digital Twin' was first used by NASA to improve a simulation process of a physical model of a spacecraft in 2010. The term has ever since permeated into manufacturing and subsequently to the AEC industry and has enjoyed broader acceptance and embracement.

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