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Construction Transformation—Connecting Sustainability (Ends) and New Technology (Means)

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CONSTRUCTION TRANSFORMATION — CONNECTING SUSTAINABILITY (ENDS) AND NEW TECHNOLOGY (MEANS)

ABSTRACT

This paper sets out a research agenda for the transformation of the architecture, engineering, and construction (AEC) sector toward sustainability by leveraging developing technological capabilities. Based on the review of (1) research discourses considering what is possible, (2) business discourses on what is profitable, and (3) policy discourses considering what is desirable, we find weak connections between the agendas on new technologies and sustainability. Addressing this shortcoming, there is imminent potential (and need) for connecting two agendas through aligning research, businesses, and policies. To support this approach, we propose a framework for understanding construction transformation along two dimensions: 1) the industry's transformation of society, and 2) the transformation of the industry. We also discuss relevant theoretical frameworks for further research, including systems thinking and project organizing.

KEYWORDS: Transformation, Technology, Sustainability, Innovation

BACKGROUND

Global society relies on our ability to construct buildings and infrastructure. Construction has been the key sector for creating the modern societies of developed countries (Thuesen *et al.* 2009), a position that developing countries also rightfully strive for. With continuing population growth and rapid urbanization (IPCC 2018), global needs for housing, schools, transport, and energy infrastructure continue to rise. However, current construction practices are inherently unsustainable and cannot be considered blueprints for the rise of the developing world (Chalmers 2014).

According to O'Neill *et al.* (2018), developed countries such as Denmark and the United States (US) are generally considered sustainable regarding economic and social dimensions but not in the environmental dimension. For an absolute understanding of sustainability, evaluating sustainability not just relative to other solutions, but against the carrying capacity the plant, Denmark and the US exceed six and seven of the identified planetary boundaries, respectively. In comparison, developing countries such as Vietnam and Sri Lanka exceed one and none of those boundaries, respectively. The transgression of planetary boundaries by developed countries is substantial for two important parameters in particular: CO_2-equivalent emissions and material footprint (O'Neill *et al.* 2018).

Recent simulations from the Stockholm Resilience Centre found that only bold transformative change will allow us to create a sustainable society beyond 2050 within the safe operating space of our planet's boundaries (Randers *et al.* 2018). This finding has significant implications for the AEC sector.

In developed countries such as the US and Denmark, construction is one of the most resource-intensive sectors. In Denmark, the sector accounts for 30% of waste production, 40% of material consumption, and 40% of energy consumption (Statistics Denmark 2018, Energistyrelsen 2015). Similarly, in the US, the sector accounts for 43% of waste production (EPA 2017), 72% of non-fuel material consumption (Matos 2017), and 39% of energy consumption (EIA 2020). Evaluating state-of-the art construction practices in Denmark, Brejnrod *et al.* (2017) estimate that "absolute sustainability can be obtained by reducing the impacts from construction by 89%, use phase energy consumption by 80%, and the living area by 60%" (p. 2).

While the AEC sector has successfully—but unsustainably—constructed the buildings and infrastructures of our modern lives, it is now facing fundamental challenges in the use of resources coupled (MacArthur 2015) with limited productivity growth (Changali *et al.* 2015 & Statistics Denmark 2018). While productivity has increased in other industries, it has been stagnating in the construction industry for the past decade. Recently, the construction industry has been declared ripe for disruption (Ernstsen *et al.* 2018). Disruption is anticipated as the AEC sector is characterized as being costly, resistant to innovation, competing fiercely on price, and delivering low-quality solutions (Barbosa *et al.* 2017). In response to the sector situation, companies are investing in new and emerging technologies such as augmented reality, robotics, virtual design and construction, 3D printing, digital supply-chain integration, and automation. These technologies are believed to be core forces in the disruption, promising the transformation of the sector. The question is, in what direction will this transformation drive the AEC sector?

This situation suggests we are on the verge of a new construction reality in which two macro-trends should converge: the need for sustainability and new disruptive technologies that can transform the products, processes, and organizations of construction.

The purpose of this paper is to outline a research agenda on the transformation of construction toward sustainability by leveraging developing technological capabilities.

We approach this aim by integrating a literature review on sustainability and new technologies in the AEC industry with relevant theoretical lenses for further exploration of the challenges to and solutions for construction transformation. We begin by outlining the methodology for reviewing the literature, followed by a presentation of three discourses represented in three domains. Based on this approach, we then introduce the framework for construction transformation and conclude with a discussion of the relevant theoretical frameworks.

METHODOLOGY

The two mega-trends mentioned above regarding new technologies and sustainability influence the transformation of construction in various ways. Inspired by Ernstsen *et al.* (forthcoming), we categorized central actors into three domains of discourse, each representing powerful drivers of construction. The three domains are: (1) research discourses driven by researchers and innovators considering what is possible; (2) business discourses created and promoted by management consultancies considering what is profitable; and (3) policy discourses developed by governmental and international bodies considering what is desirable.

For each domain, we identified central texts concerning new technologies and sustainability relevant for understanding the construction sectors in the US and Denmark.

Given the publication practices and amount of research on technologies and sustainability related to construction transformation, we conducted a holistic review based on a meta-analysis of Web of Science (WOS) articles and their citations. The WOS searches generally returned smaller lists of results compared with, for example, Scopus and Google Scholar (GS). Within the field of engineering and computer science, Martin-Martin *et al.* (2018) found that WOS identified 52% of the citations, compared with 63% for Scopus and 93% for GS. While this lower return is a limitation, we do not consider it decisive since we want to explore the broader organization of discourses around technology and sustainability in construction. We used the WOS to acknowledge the role of the technical sciences in developing technologies influencing the industry.

Table 1: Technology and sustainability concepts

Technology concepts	**Sustainability concepts**
3d print	bream
augmented reality	circular econom*
big data	energy efficien*
bim	green build*
block chain	indoor climate
digital twin	iso 14001
iot	lca
lean construction	leed
machine learning	life cycle cost
modular*	life cycle assessment
off site	natural resources
robot	occupan*
virtual reality	safety
	stakeholder
	sustainable development goals

* is used to include different versions/spellings of the search result

The analysis was completed using the following process:

1. Identifying key concepts (see Table 1) within sustainability and new technology based on central publications. For example, the concept “lean construction” was included because it takes a holistic view of the effective use of technologies, not just technologies in and of themselves. The term is concerned not only with what technologies can do, but also with how to use technologies and why, when, and by whom.
2. Searching the WOS for articles based on each of the key concepts, with the boundary conditions related to either the “construction industry” or the “built environment” *TS=("CONCEPT") AND TS=("construction industry" OR "built environment").*
3. Importing all the search results in the WOS Viewer to analyze (normalized) citations (the recent being the most relevant).
4. Identifying patterns using Gephi by adjusting the modularity and running its visualization algorithm.

Figure 1 illustrates the resulting 2,942 articles (nodes) and their most important citations (7,928 links). Larger nodes represent articles that are cited more frequently, and their relative placement is based on their connectedness to the other articles. Articles placed close to each other share a substantial number of citations, whereas articles further apart share fewer.

LITERATURE REVIEW

Research-based discourses on what is possible

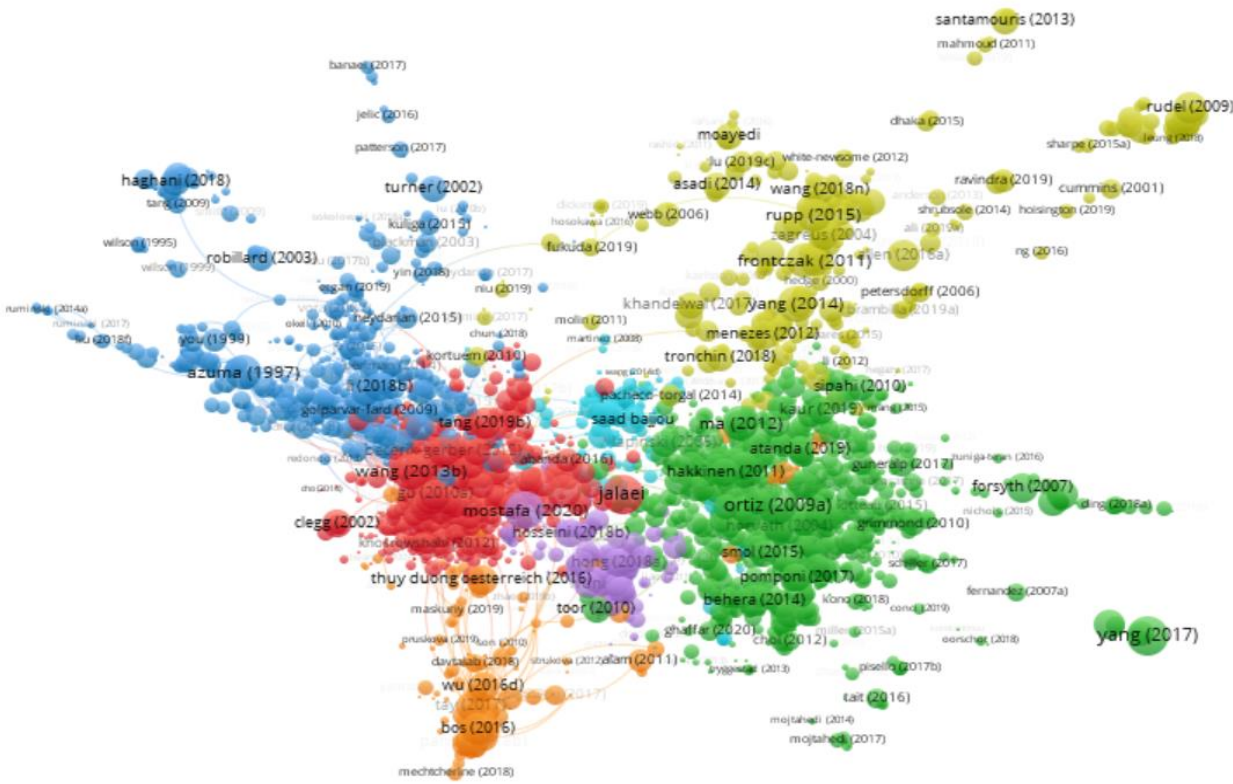

Figure 1: Research-based discourses covering technology and sustainability

This figure demonstrates a broad organization of research-based discourses in a range of clusters (colors). The clusters represent areas with a high degree of citations shared between articles. Thus, the clusters can be interpreted as a scientific domain or a superset of connected domains. The green cluster represents the sustainability domain, and the yellow the indoor environment, whereas other colors represent the technology domains such as VR, BIM, lean construction, offsite manufacturing, and robotics. Table 2 lists the key characteristics of the clusters.

Table 2: Clusters of research-based discourses

Cluster	Central topics	No. of articles
Sustainability	lca, green building, energy efficiency, life cycle	955
BIM	bim, big data, 3d, facility management,	652
AR/VR	ar/vr, safety, training	542
Indoor climate	comfort, indoor environment, occupancy, ventilation	339
Offsite	prefabrication, modern methods, modular	143
Lean processes	lean construction, assembly, logistics	139
Robotics	3d print, robotics	132

The overview generally indicates a weak connection between the sustainability and technology discourses represented in the number of links (citations) between clusters. The main component of research activities within the discourses happens at the center of the clusters. Exemplary articles here are Gu and London's (2010) investigation of "BIM adoption in the AEC industry" and the review by Ortiz *et al.* (2009) of recent development of lifecycle assessment (LCA) in the construction industry. Each discourse is more or less connected, as illustrated by the number of citations within the clusters. Although the clusters for technologies are well integrated, this is not the case for the sustainability cluster to the same extent. In the sustainability cluster, the details of the network reveal the limited visibility of more radical understandings of sustainability, such as those pertaining to the circular economy and planetary boundaries.

The different clusters are connected by boundary-spanning articles such as the integration by Jalaei *et al.* (2019) of LCA and BIM to manage and optimize construction waste. While these articles represent key connections between the sustainability and technology discourses, they are far outnumbered by articles within the clusters. As is to be expected, most research focuses on developing the discipline of a certain cluster rather than connecting agendas across the scientific disciplines. The boundary-spanning articles further shape the overall discursive landscape by collocating clusters with shared articles and agendas. Specifically, it is worth noting the relatively more proximal placement of the lean and offsite discourses to sustainability compared with robotics and AR and VR. One explanation could be lean's holistic mindset and its strong systems orientation with its "respect for people" focus, stressing value generation and waste elimination. The closeness further suggests that these domains can be central in bridging the technology and sustainability discourses in the future. Furthermore, both the lean and offsite clusters have an inherent focus on business processes, suggesting a special role for business discourses in connecting technologies and sustainability.

Business discourses: what is profitable

To document current business discourses, we reviewed central publications from consultancies and the World Economic Forum (WEF). The construction industry has, in recent years, increasingly been an object of attention from high-profile consultancies proposing change agendas for construction and arguing that the sector is ripe for disruption (e.g., Ernstsen *et al.* 2018). Building on Teicholz *et al.* (2001), research on productivity, and an extension to more than 30 industries, McKinsey found that productivity development in construction is "remarkably poor," especially in developed countries such as the US and Denmark (Barbosa *et al*. 2017). While McKinsey conceptualization is arguable, pursuing continuous improvement is relevant in many possible directions, not least of which should be aiming for greater sustainability. The emphasis on productivity is also present in the WEF (2016), although they add that the construction industry's significant societal and environmental impact creates a substantial case for digitally transforming the sector. In a later publication, they identify the construction industry's key challenges as follows (WEF 2017, p. 3):

1. Project delivery—Creating certainty to deliver on time and on budget, and improving the productivity of the construction sector
2. Lifecycle performance—Reducing the lifecycle costs of assets and designing for reuse
3. Sustainability—Achieving carbon neutral assets and reducing waste during construction
4. Affordability—Creating high-quality, affordable infrastructure and housing
5. Disaster resilience—Making infrastructure and buildings resilient against climate change and natural disasters

6. Flexibility, liveability, and well-being—Creating infrastructure and buildings that improve the well-being of end-users

Accordingly, the WEF articulates a broader agenda for change beyond merely addressing economic measures and include all three dimensions of sustainability. However, most publications emphasize the role of technology. This emphasis is illustrated in Figure 2, which presents the WEF's framework for transforming the industry's processes using various digital technologies (Gerbert *et al.* 2016).

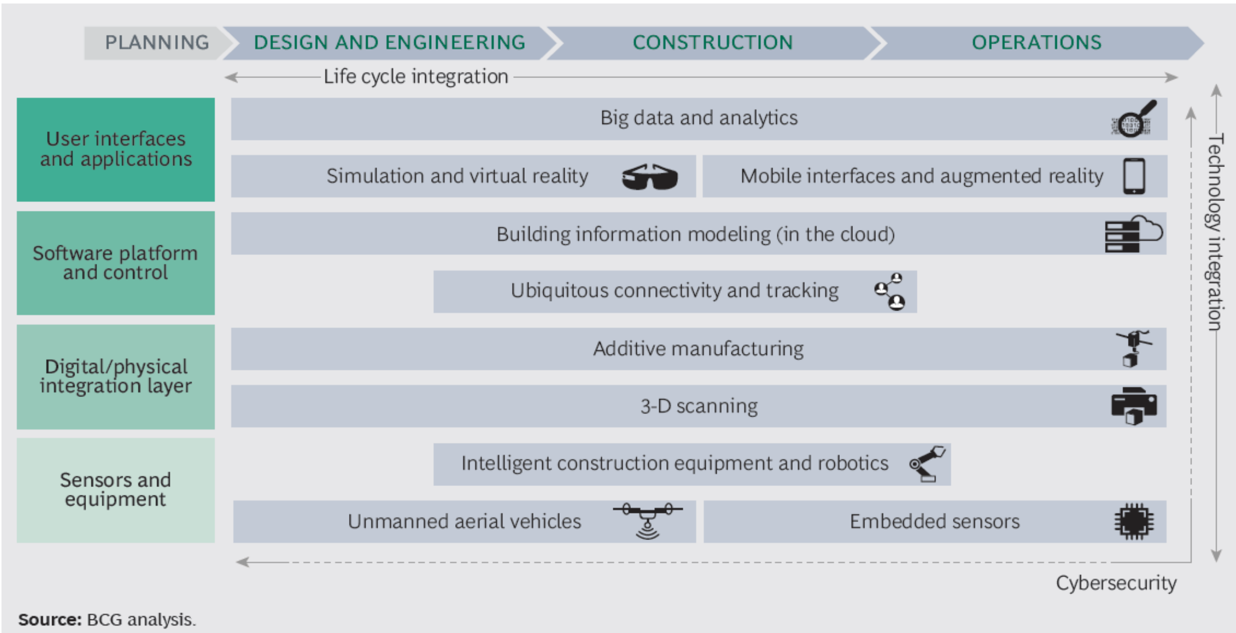

Figure 2: Technology integration in the construction life cycle according to the WEF and Boston Consulting Group (Gerbert *et al*. 2016)

Building on the WEF's framework, a Danish innovation network of construction companies (Innobyg) mapped use-cases of new technologies along the lifecycle of buildings. They found a wide adoption of technologies in the companies and in all phases under study, except for recycling. While the inclusion of recycling as a specific phase indicates attention toward sustainability, which is absent in the WEF framework, the number of cases targeting recycling in Innobyg (2019) reveals a limited connection to the sustainability agenda.

However, transforming construction is not simply about adopting new technologies; it also requires changing regulations, rethinking commercial terms and incentives (including contractual structures), and standardizing processes. McKinsey identifies rising investments in construction technology firms amounting to $10 billion from 2011 through early 2017 (Blanco *et al.* 2017). Building upon this insight, Blanco *et al.* (2018) analyzed the expanding construction technology landscape to identify trends and constellations around established and emerging use-cases, which are illustrated in the following network graph (Figure 3). Their understanding of a use-case stems from IT development in how the technology is embedded in organizational practices. A use-case is, therefore, not simply a technology but a specific application of technologies (IT) to an organizational process. The nodes of the network represent the use-cases, and the thickness of their connections indicates a greater number of IT companies offering the connected technologies simultaneously.

The network graph maps the intricacy of the established use-cases organized in three clusters – (1) back-office, (2) digital collaboration, and (3) on-site execution – and how they are connected to constellations of emerging use-cases within (a) supply-chain optimization and marketplace, (b) 3D printing, modularization, and robotics, (c) artificial intelligence and analytics, and (d) digital twins. It is apparent from the graph that the established use-cases are highly interconnected, whereas the emerging ones are less so. The network creates a holistic overview of where technologies might transform the practices of construction, a perspective that is missing in the research-driven discourses. The network thereby provides a rare overview of the complexity of the present and potential futures of construction that construction professionals must navigate. Especially interesting are the constellations of the emerging use-cases, as they represent a future orientation that is not present in the established use-cases. However, the analysis fails to explore how these constellations of technologies integrate in different visions for the future of the industry and, in particular, in relation to sustainability.

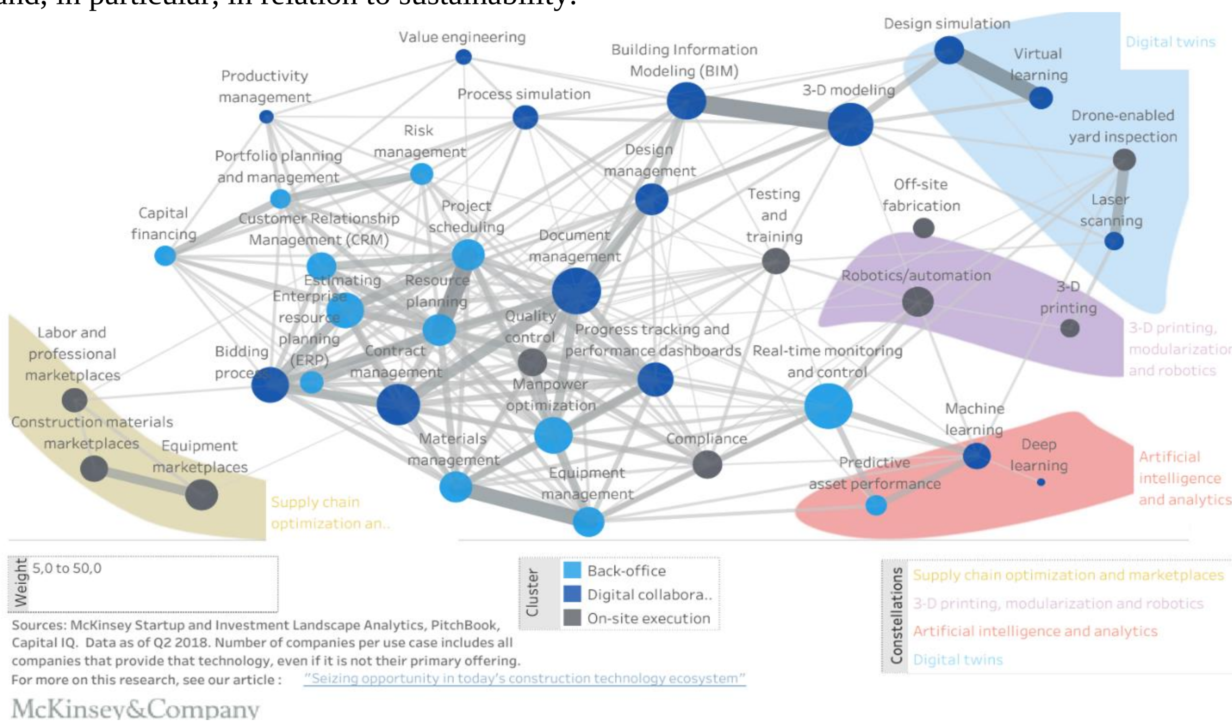

Figure 3: Construction technology system according to McKinsey (Blanco *et al*. 2018)

Further conceptualizing the future of construction, Bartlett *et al.* (2019) identified archetypes for emerging engineering and construction companies. In addition to suppliers of equipment and materials, these archetypes include “platform integrators [providing] the platforms to design and manage large assets across their life cycle... Vertically integrated designers and manufacturers [owning] the design, specification, full fabrication and assembly processes…[and] Lean executors [based] on traditional trade contractors” (p. 4). Finally, Blanco *et al.* (2019) identified governments as a key driver in facilitating the adoption of digital technologies by leveraging the regulatory powers to set standards for the industry and the purchasing power to implement standards.

Policy discourses: what is desirable

The construction industry has traditionally been important to governments for several reasons. One reason is that the products of the industry directly create the physical infrastructures of society, and another is that the industry is an economical engine of society through its many employees. However, over the past century, the role of construction in society changed. Following World War II, construction was used as a strategic sector to address growing urbanization and high unemployment in the modernization of societies (Gottlieb and Frederiksen 2019). This use is demonstrated by the rapid increase of construction material consumption in the decades between 1945 and 2005 (Figure 4).

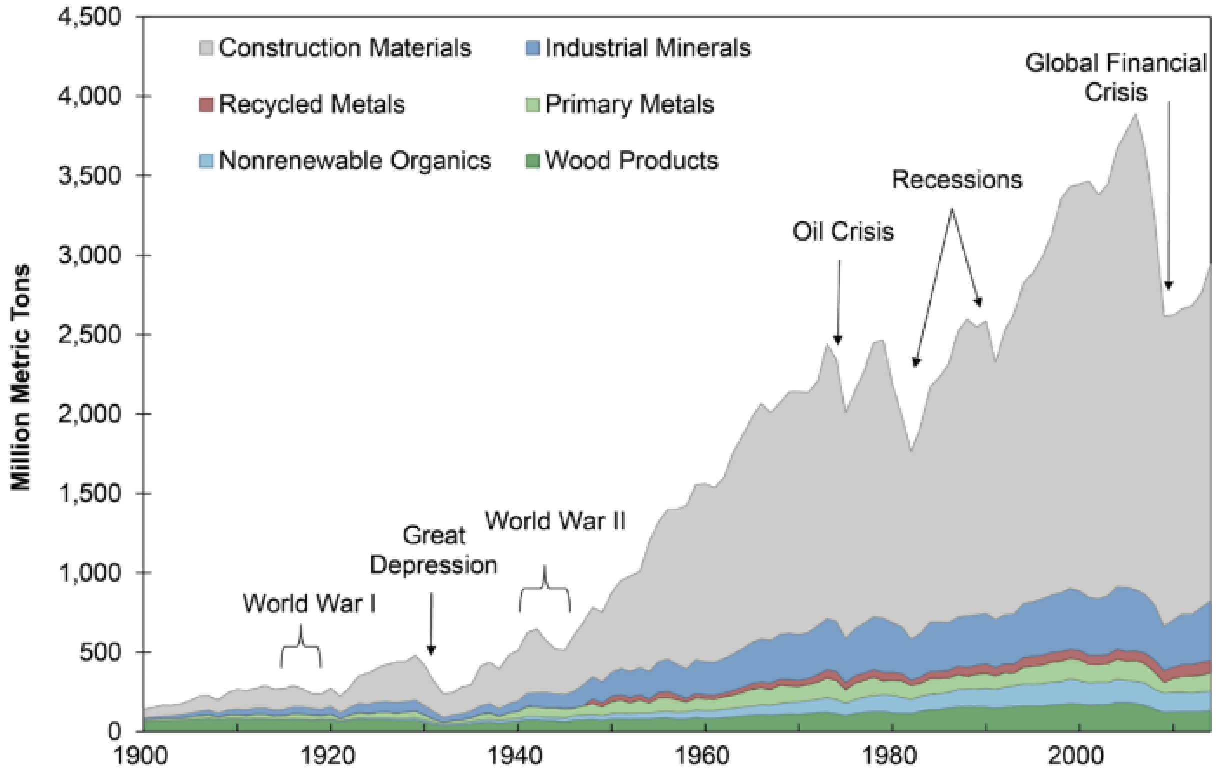

Figure 4: U.S. non-fuel material consumption, 1900–2014 (Matos 2017)

Inspired by scientific management and through top-down governmental programs over these decades, the products, processes, and organizations of construction changed. This change also created frameworks for sectorial standards, building codes, and policies that have influenced the industry ever since. Later in the 80'ies, the sector was problematized for its limited productivity and, thus, inferior relevance in the drive for economic growth—investment in construction could not compete with other sectors. In this period, digital technologies and offsite manufacturing were introduced as enablers for productivity development for building processes. Paradoxically, as work moved offsite to manufacturers, and was, thus, no longer counted as construction, a nuanced understanding of construction productivity was required. This situation was mirrored in the Danish commission for productivity development, which found the existing dataset to be inefficient for evaluating such development (Produktivitetskommissionen 2014). In parallel to the focus on productivity, building codes were gradually changed, increasing the energy efficiency of the constructed buildings, initially as a response to the oil crisis.

The policies governing construction today continue to frame energy efficiency and productivity as central agendas, but their context and focus have changed. Although international standards today pervade the industry, construction has traditionally been considered a domestic industry. However, global technological development, increasing diffusion of international standards, and increased focus on global challenges such as climate change have forced politicians and industry to rethink construction. Energy efficiency is not merely a matter of saving energy in response to an oil crisis, but it must also focus on reducing emissions of greenhouse gases. Today, construction is an important driver for sustainable development (e.g., Thuesen & Opoku 2018). This importance is reflected in the upcoming regulatory framework for construction in the European Union, to be implemented in all member states, including Denmark. Based on this framework, construction should consider the following (European Commission 2020):

1. Greenhouse gas emissions throughout the building's lifecycle
2. Resource-efficient and circular material lifecycles
3. Efficient use of water resources
4. Healthy and comfortable spaces
5. Adaptation and resilience to climate change
6. Lifecycle cost and value

The regulatory framework to drive sustainable development in the construction sector in the US is a patchwork of national, state, and local regulations, building codes, design guidelines, recommendations, and incentive programs. This patchwork addresses the needs for energy efficiency, material recycling and reuse, building occupant well-being, greenhouse gas emissions, and other regional or local considerations. Examples of these US regulations, codes, guidelines, and incentive programs include:

1. Leadership in Energy and Environmental Design (LEED) (USGBC 2020)
2. California Building Energy Efficiency Standards (CEC 2018)
3. ANSI/ASHRAE/IES Standard 90.1 – Energy Standards for Buildings (ASHRAE 2019)
4. WELL Building Standard (IBWI 2016)
5. ENERGY STAR (USDOE 2020)
6. Consumers Energy Net Zero Energy Program (Consumers Energy 2020)
7. California Cap-and-Trade Program (ARB 2015)

Considering the development in policy discourses over the years, it is evident that the AEC sector has always played a central role in society, although discerning "what is desirable" has changed from focusing on addressing urbanization and employing unskilled labor to productivity development, energy efficiency, indoor climate, and, lately, circular economy.

To create an overview of our initial review, we summarized the three domains in Table 3.

Table 3: What is possible, profitable, and desirable

What is possible	**What is profitable**	**What is desirable**
Research discourses driven by researchers and innovators	Business discourses created and promoted by management consultancies	Policy discourses pushed forward by governmental and international bodies
● Weak connection between technology and sustainability ● Discourses on technology more connected than those on sustainability ● Boundary article spans represent important brokers ● Lean construction and offsite manufacturing represent clusters bridging technology and sustainability domains ● Central role for business discourses	● Different scopes of discourses. The WEF includes social and environment measures. McKinsey mainly address economic measures. ● All articulate the productivity challenge ● (Digital) technologies play an important role but are mainly connected to productivity ● Different technologies transform different parts of the value chain ● Different maturity of technologies and use-cases ● Central role for policy discourses	● Technology has always played a role in the transformation of construction ● Productivity challenges still important ● Increasing focus on environment and social targets ● Move from emphasis on energy efficiency to circular economy (EU) ● Global awareness

FRAMEWORK FOR CONSTRUCTION TRANSFORMATION

The literature review suggests the potential for integrating the two agendas on sustainability and new technology through the different discourses. This integration requires a mindset connecting means and ends in the appropriate manner. Consequently, we must regard sustainability as ends for our ingenuity, including all three dimensions of sustainability—not just the economy. In contrast, technologies should be viewed as means that we must learn to leverage and operationalize effectively—not as ends in themselves.

This approach translates into two dimensions of construction transformation to operationalize and evaluate further: (1) the transformative power of construction through the sector's effect on society; and (2) the transformation of construction practices within the sector to support the realization of a sustainable society. These dimensions are illustrated and explained in Figure 5 and Table 4.

Developing a research agenda along these two dimensions for construction transformation calls for systems-based theorizing that, without being deterministic, connects the various levels of the built environment. Such development further requires an operationalization of projects as drivers for industry and societal change within a mindset that balances value-creation with resource scarcity. Therefore, we suggest two theoretical streams, each discussed in turn: (1) systems thinking for understanding and modeling the complex and uncertain nature of construction processes and products; and (2) project organizing for operationalizing the design, production, maintenance, and recycling of buildings and infrastructures, but also for realizing innovation.

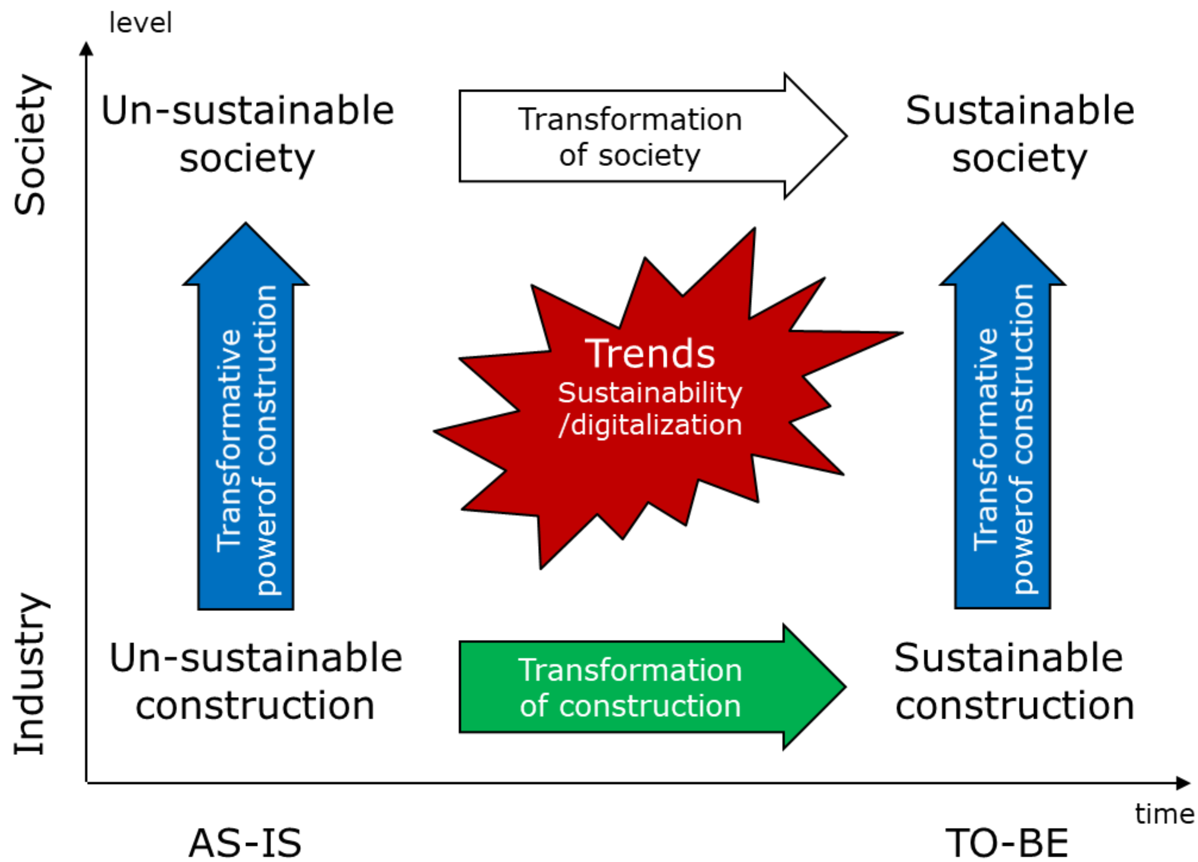

Figure 5: Framework for construction transformation

Table 4: Dimensions, challenges, and perspectives on construction transformation

	The transformation of construction (technology)	**The transformative power of construction (sustainability)**
Challenges	• We must change our current practices • Minimizing the consumption of resources • Maintaining/increasing value production	• We must understand our impact • Evaluating the economical, societal, and environmental impact of construction • Identify the urgent societal challenges and mobilize resources
Systems thinking	Understanding and modeling the production systems of construction	Understanding and modeling the building and materials, and how they work in a broader system
Project organizing	Projects as drivers for industry change	Projects as drivers for societal change

Systems thinking

Documenting and evaluating the impact of construction is not an easy task given the technical complexity, social intricacy, and elaborate processes of the built environment. As such, the built environment can be considered a system of systems. The value of construction to society is not generated by any one element of these systems but only when the system elements work together: for example, today's buildings consist of tons of materials and subsystems and are further embedded in a complex network of supporting infrastructures for electricity, heating, waster, water, etc. This form makes these systems large—they become complex and, in their entirety, they require substantial capital investment representing substantial societal value. For example, buildings in Denmark represent 66% of the national balance sheet (DST 2018). This figure implies long lifecycles, as the systems cannot be easily replaced but instead evolve over time in a process of continuous renewal and maintenance to ensure relevance. However, the value represented by these systems should be evaluated against their massive utilization and consumption of resources.

To conceptualize the impact and transformation of construction, we suggest a strategy rooted in systems thinking that extends the SIMSS (Sustainable Infrastructure Materials, Structures, and Systems) framework (Lepech 2006) with the mindset of engineering systems (DeWeck, Roos, & Magee, 2011). The SIMSS framework evaluates the performance of the built environment from the bottom-up by modeling the design, materiality, and processes at various levels from materials -> buildings -> systems. The engineering systems mindset introduces the social intricacy of the systems in the built environment and how they fulfill important functions in society. In the resulting mindset, the built environment is not merely technical systems but is closely linked to the way people use it and the way it influences people in return. Thus, the system becomes socio-technical, as illustrated in Figure 6.

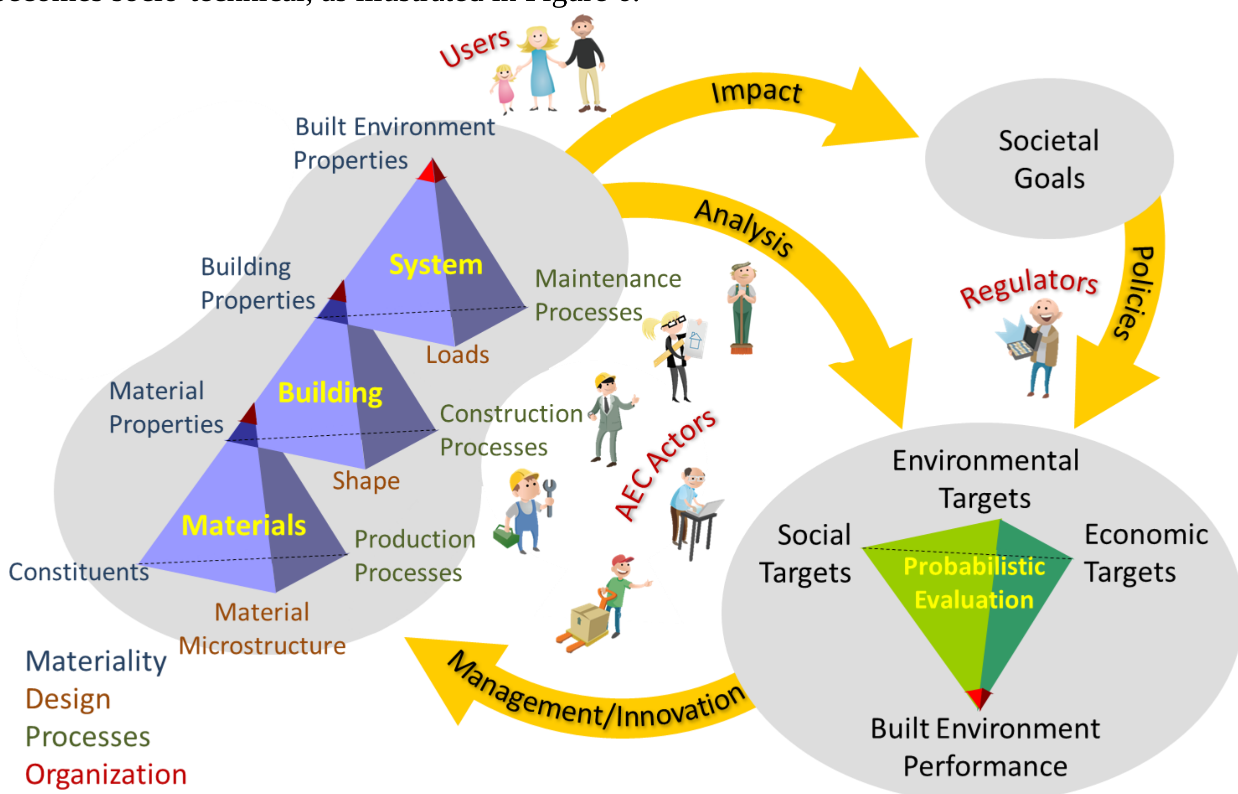

Figure 6: Engineering systems from materials to the built environment

The resulting framework supports construction transformation by enabling the modeling of the materiality, design, processes, and organization of construction. Combined with LCA and lifecycle costing (LCC), the framework can evaluate the impact of the construction sector at various levels, thereby supporting the realization of societal goals that can be enforced by various policies. In addition, the framework can evaluate how new technologies and sustainability concepts influence different parts of the systems. For example, will a new insulation material mainly be relevant in the material pyramid? Will IOT have the potential to influence all levels in the built environment and the supporting processes? However, although the framework helps document the progress of construction transformation, it does not facilitate the actual change. This change is achieved by organizing projects.

Project organizing

Project organizing is central to the realization and transformation of these systems in two fundamental ways:

Projects as a driver for societal change (the transformative power of construction)

Given the size, complexities, and context of construction, projects have become the main mode of production. This mode is struggling with its limited ability to deliver the requested quality on time and budget—also termed project efficiency. This issue is believed to be one of the root causes for the low productivity development in the sector. Lean construction (Koskela 1992, Koskela *et al.* 2002) addresses this challenge, improving project-production system performance based on respect for people, flow, value-creation, and waste elimination.

Traditionally, productivity has been considered a means for growth and prosperity via optimizing output vs input of processes. While this view is certainly still important, the narrow definition of productivity can be criticized for not measuring the real impact of projects. This point resonates with the recent development in the project management community that traditionally focused on the execution of projects to generate agreed deliverables but now displays an increasing interest in the broader context for projects and their effectiveness, highlighting the fuzzy front-end, benefit realization (e.g., Morris 2013), and value to a broader set of stakeholders (Drevland 2019).

The call to understand the transformative power of construction requires further extensions of the frameworks for qualifying, evaluating, and documenting impacts of projects, as exemplified in our systems model above. This requirement includes not only a wider scope and value generation of the projects (Evans *et al.* 1998, Fischer *et al.* 2017), but also serious consideration of the consumption of resources—especially in the light of absolute measures of sustainability, such as the planetary boundaries (O'Neill *et al.* 2018, Randers *et al.* 2018). Lifecycle costing and LCA have proven instrumental through standardized tools (e.g., ISO 14044 and ISO 15686-5) specifically designed for qualifying and quantifying total economic and environmental impacts across the lifecycles of systems (Hauschild *et al*. 2018). While both LCC and LCA generally connect well to the mindset of project organizing, they remain incomplete in terms of qualifying the social dimension and absolute measures of sustainability.

Projects as drivers for sectorial change (transformation of construction)

Projects also play a central role in transforming the sector. For example, work on strategic niche management (Kemp *et al.* 1998) and the multi-level perspective (Schot & Geels 2008) suggest that projects are the driving force in niche formation processes and, thereby, the transitioning of sectors. Programs are usually considered to be vehicles for wider impacts but fail to address the complexities and emergent characteristics of sector transformation. The concepts of lineage (Midler 2013) and murmuration (Koch-Ørvad *et al.* 2018) have been suggested as frames for conceptualizing more fluid ways of organizing change through a series of smaller, explorative projects. In this sense, projects become a mode of innovation in which new technologies reconfigure the practices of the sector. Consequently, projects are key for transforming the existing project-based production of the sector into closed loop systems—circular construction platforms.

CONCLUSION

In this paper, we outlined a research agenda on the transformation of construction toward sustainability, leveraging emerging technologies. Through a literature review of research, business, and policy discourses related to the construction sectors in Denmark and the US, we found limited connections between the development of new technologies and sustainability. While most research discourses emphasize disciplinary research into different forms of technologies or sustainability, research clusters regarding lean construction and offsite manufacturing act as boundary-spanning themes. Consequently, business discourses must play an important role in connecting new technologies and sustainability. Unfortunately, the review of business discourses found a major emphasis on new technologies as a driver for productivity development, (unintentionally) downplaying social and environmental dimensions of sustainability. This economic rationality also governs the policy discourses, although they increasingly articulate the environmental dimension. Thus, there is imminent potential (and need) for connecting these two agendas in the transformation of construction through aligning research, businesses, and policies. Consequently we propose a framework for understanding construction transformation along two dimensions: (1) the transformative power of construction through the sector's effect on society; and (2) the transformation of construction practices within the sector to support the realization of a sustainable society. This approach requires at least two theoretical perspectives: 1) systems thinking, because we need to understand and model the buildings and the processes through which we are producing them; and 2) project organizing, because projects are the mode of production in and innovation of the sector. Thereby the paper contributes to the foundation for re-building sustainable societies.

REFERENCES:

ASHRAE (2019) ANSI/ASHRAE/IES Standard 90.1-2019 Energy Standard for Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, Georgia, USA. 357 pages.

ARB (2015) Overview of ARB Emissions Trading Program. California Environmental Protection Agency Air Resources Board. Sacramento, California, USA. https://ww2.arb.ca.gov/sites/default/files/classic//cc/capandtrade/guidance/cap_trade_overview.pdf

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., Bertram, N., and Brown, S. (2017). *Reinventing Construction: A Route To Higher Productivity*. *McKinsey Global Institute*.

Bartlett, K., Blanco, J., Rockhill, D., & Strube, G. 2019 Breaking the mold-The construction players of the future, Global Infrastructure Initiative

Blanco, J., Mullin, A., Pandya, K. & Sridhar, M. (2017) The new age of engineering and construction technology, Capital Projects and Infrastructure July 2017

Blanco, J., Mullin, A., Pandya, K., Parsons, M. & Ribeirinho, M. (2018) Seizing opportunity in construction technology, Capital Projects and Infrastructure September 2018

Brejnrod, K. N., Kalbar, P., Petersen, S., & Birkved, M. (2017). The absolute environmental performance of buildings. Building and environment, 119, 87-98.

CEC (2018) 2019 Building Energy Efficiency Standards for Residential and Nonresidential Buildings. California Energy Commission, Sacramento, California, USA. Publication No. CEC-400-2018-020-CMF. 325 pages.

Chalmers, P., 2014. *Climate Change: Implications for Buildings*. Cambridge Institute for Sustainability Leadership.

Changali, S., Mohammad, A. and van Nieuwland, M. (2015). The construction productivity imperative. McKinsey Insights. McKinsey & Company. July 2015

Consumers Energy (2020) Zero Net Energy (ZNE) Companion Program. Consumers Energy Company. Jackson, Michigan, USA. https://www.consumersenergy.com/-/media/CE/Documents/Energy%20Efficiency/business/zne-flyer.ashx?la=en&hash=2DC9650D9EC4053AB4FD417635F9C8B41B182730

Dieter, C.A., Maupin, M.A., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2018, Estimated use of water in the United States in 2015: U.S. Geological Survey Circular 1441, 65 p., https://doi.org/10.3133/cir1441

De Weck, O. L., Roos, D., & Magee, C. L. (2011). *Engineering systems: Meeting human needs in a complex technological world*. MIT Press.

Drevland, F.O. (2019) Optimising Construction Projects as Value Delivery Systems - Expanding the theoretical foundation. Doctoral thesis, NTNU

DST (2018), NASK: Akkumulations- og statuskonti, investering og beholdning af faste aktiver, efter beholdning / strøm, aktiv og sektor, Danmarks Statistik

EIA (2020) How much energy is consumed in U.S. buildings? https://www.eia.gov/tools/faqs/faq.php?id=86&t=1

Energistyrelsen. (2015). *Bæredygtigt byggeri [Sustainable construction]*. Energistyrelsen.

EPA (2017) The State of the Practice of Construction and Demolition Material Recovery, U.S. Environmental Protection Agency

Ernstsen, S. K., Whyte, J. Thuesen, C. & Maier, A. (forthcoming) How Innovation Champions Frame the Future: Three Visions for Digital Transformation of Construction. *Journal of Construction Engineering and Management*

Ernstsen, S.K. Maier, A. Larsen, L.R. & Thuesen, C. (2018) Is Construction ripe for disruption, Working paper ARCOM 2018 Conference, Belfast, UK, 3-5 September 2018.

European Commission (2020) *Building sustainability performance - Level(s)* https://ec.europa.eu/environment/eussd/buildings.htm

Evans, R, R Haryott, N Haste, & A Jones (1998) *The long-term costs of owning and using buildings*. London: Royal Academy of Engineering.

Gerbert, P., Castagnino, S., Rothballer, C., Renz, A. & Filitz, R. (2016) Digital in Engineering and Construction, The Transformative Power of Building Information Modeling, Boston Consulting Group, March 2016

Gottlieb, S. C., & Frederiksen, N. (2020). Deregulation as socio-spatial transformation: Dimensions and consequences of shifting governmentalities in the Danish construction industry. *Environment and Planning C: Politics and Space*, *38*(3), 484–502.

Gu, N., & London, K. (2010). Understanding and facilitating BIM adoption in the AEC industry. *Automation in construction*, *19*(8), 988-999.

IBWI (2016) WELL Building Standard.v1. Delos Living, LLC. New York, New York, USA. https://standard.wellcertified.com/well

Innobyg (2019) BUILD 4.0 – Værdiskabelse med nye teknologier i den danske byggebranche, Innovations netværket for bæredygtigt byggeri. https://issuu.com/www.innobyg.dk/docs/build40mapping

IPCC, 2018. *Global warming of 1.5°C An IPCC Special Report*.

Kemp, R., Schot, J., & Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. *Technology analysis & strategic management*, 10(2), 175-198.

Koch-Ørvad, N, Thuesen, C, Koch, C and Berker, T (2018) Murmuration as Metaphor for Sustainable Innovation Processes In: Gorse, C and Neilson, C J (Eds) Proceeding of the 34th Annual ARCOM Conference, 3-5 September 2018, Belfast, UK, Association of Researchers in Construction Management, 179-188.

Koskela, L., Howell, G., Ballard, G., & Tommelein, I. (2002). The foundations of lean construction. *Design and construction: Building in value*, *291*, 211-226.

Lepech, M., G.A. Keoleian, and V.C. Li (2007) "Integrated Structure and Materials Design for Sustainable Concrete Transportation Infrastructure" In *International Society for Industrial Ecology Conference 2007*. Toronto, Canada. June 17-20, 2007. Pages 17-20.Lepech, M. (2006) "A Paradigm for Integrated Structures and Materials Design for Sustainable Transportation Infrastructure" PhD Dissertation. Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor.

MacArthur Foundation (2015)Potential For Denmark As A Circular Economy A Case Study From: Delivering The Circular Economy – A Toolkit For Policy Makers, Ellen MacArthur Foundation

Matos, G., (2017) Use of raw materials in the United States from 1900 through 2014: U.S. Geological Survey (USGS) Fact Sheet 2017–3062, 6 p.

McIntyre, A. (2007). *Participatory action research* (Vol. 52). Sage Publications.

Midler, C. (2013). Implementing a low-end disruption strategy through multiproject lineage management: The Logan case. *Project Management Journal*, *44*(5), 24-35.

Morris, P. W. (2013). Reconstructing project management. John Wiley & Sons.

O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability*, *1*(2), 88–95.

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and building materials*, *23*(1), 28-39.

Produktivitets kommissionen (2014) "Det handler om velstand og velfærd", Produktivitetskommissionen, DK

Randers, J., Rockström, J., Stoknes, E., Golüke, U., Collste, D., & Cornell, S. (2018). *Transformation is feasible*. Stockholm Resilience Centre.

Schot, J., & Geels, F. W. (2008). Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. *Technology analysis & strategic management*, *20*(5), 537-554.

Statistics Denmark, (2018). *Green National Accounts for Denmark 2015-2016*.

Teicholz, P., Goodrum, P. M., & Haas, C. T. (2001). US construction labor productivity trends, 1970–1998. *Journal of Construction Engineering and Management*, *127*(5), 427-429.

Thuesen, C. & Opoku, A. (2018). A CALL FOR ACTION: Constructing solutions for the sustainable development goals, Working paper ARCOM 2018 Conference, Belfast, UK, 3-5 September 2018.

Thuesen, C., Jensen, J. S., & Gottlieb, S. C. (2009). Making the long tail work: reflections on the development of the construction industry the past 25 years. In A. Dainty (Ed.), *Proceedings 25th Annual ARCOM Conference: 7-9 September 2009.* (pp. 1111-20). Nottingham, UK:

USDOE (2020) About ENERGY STAR - 2019. United States Department of Energy. Washington, DC, USA. https://www.energystar.gov/about

USGBC (2020) Reference Guide for Building Design and Construction. US Green Building Council. Washington DC. https://www.usgbc.org/guide/bdc

WEF (2016) Shaping the Future of Construction A Breakthrough in Mindset and Technology, World Economic Forum, 2016

WEF (2017) Shaping the Future of Construction – inspiring innovators de redefine the industry, World Economic Forum, February 2017

Womack, J. P., & Jones, D. T. (1997). Lean thinking—banish waste and create wealth in your corporation. *Journal of the Operational Research Society*, *48*(11), 1148-1148.