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Is the convergence of architecture, engineering and science through design 'practice' transforming building technology research? Can new methods reorient innovation in construction?

Reorienting innovation: transdisciplinary research and building technology

Maria-Paz Gutierrez

Over fifty years ago at the RIBA's 1958 Oxford Conference, discussions about architectural research and science posed seminal questions about the very nature of creativity in architectural research and education.[1] Leslie Martin observed that research is the tool by which theory is advanced. For more than half a century, we have seen traces of scientific research fuelling the advancement of architectural knowledge and its feedback loops into practice.[2] Yet, interrogations around how architectural creativity is affected by intersections with the sciences are not new. The Bauhaus, for example, sought to integrate scientific thought in architectural education in 1936.[3] Thus, why are emerging interdisciplinary collaborations where architecture, engineering and science converge at the inception of design potentially transformative?

Increasing attempts to accelerate the pace of innovation in sustainable building technology is engendering pioneering intersections between architecture, engineering and natural science disciplines such as bioengineering and chemistry. The broad disciplinary breadth of these research processes inevitably requires mediating the diverse values, perspectives and research methodologies of disciplines that pursue innovation in different ways. However, to what extent is this new interdisciplinary convergence possibly transformative? Could it be that these processes, particularly in building technology innovation, may be influencing scientists and engineers to rethink how design problems are conceptualised and researched?

The interdisciplinary view of the architect has often been deemed the basis for innovation, as well as for architecture's unconventional and varied research methodologies. Architectural design is by essence progressive and projective. It can hardly be reduced to a singular speciality or scale of investigation. Consequently, it is ideally suited to provide a conceptual framework for the diverse and vast disciplinary criteria that must be accommodated in design formulation. Research scales of construction technologies and systems usually differ from those pursued in science and even engineering. Building technology and science are typically researched in academia from the millimetre to the metric span. On the other hand, science encompasses nano and micro scales, as well as kilometre scales for regional studies. Likewise, research timeframes and funding models in architectural practice and academia also vary substantially compared with those within science and engineering. For example, basic scientific research frequently is funded for five-year periods, while academic research in architecture typically is supported for one-year cycles. To understand the transformative potential of interdisciplinary pursuits requires an evaluation of these factors. Classifying shared and divergent investigation methods, evaluation, dissemination and collaborative models can reveal the emergence of a new collaboration ethos in building technology.

For the purpose of discussing the emerging collaborations between scientists, engineers and architects, this paper will focus on building technology and systems research. This field encompasses very distinct processes and collaboration structures – project-based implementation of building components through the exercise of: *CP* (Commercial Practice)[4], which is project-oriented; *HECP* (High End Critical Practice)[5], also project-based; and theme-based investigations in academia in *BRBT* (Basic Research on Building Technology).[6] Commercial Practice refers to the exercise of adopting innovation produced typically through R&D (Research and Development) by manufacturers (for example, DuPont) and by architectural firms. High End Critical Practice refers to the research carried out by firms of varying sizes which encompass internal research cluster units of a more or less formal nature. Yet, the research practices share the common denominator of focusing on producing building technology innovation and not adopting innovation. In addition to these research categories, the paper addresses the potential transformative nature of the recent convergence of architecture and fundamental science carried

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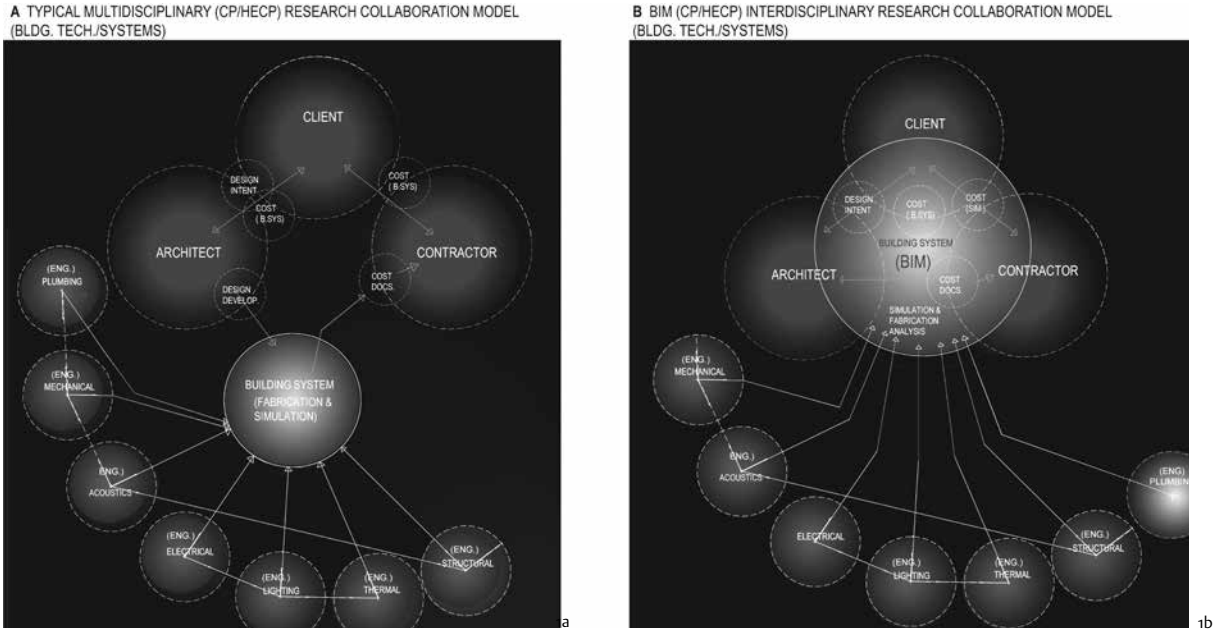
across different scales. It interrogates specifically how singular characteristics of its collaborative structures support transformative research and are potentially transdisciplinary.[7] This field is here termed as *TIBS (*Transdisciplinary Innovation Building Systems*)*.[8] The fundamental differences in the collaboration structures in these four research categories are discussed by addressing how the varying aims, motivations and investigation methods lead to, and are affected by, dissimilar collaboration structures, which shape not only the generation of new technology but knowledge itself.

The text is organised by an initial background and overview of collaboration models and building technology innovation structures applied in the construction sector, as commercial practice or high-end critical practice, and through basic research in academia. This introduction is followed by a discussion of key incentives for new interdisciplinary models, including the growing interest in user-inspired research and interdisciplinary funding programmes, as well as, computational advances in multiscale performance simulation. Subsequently, the text compares investigation methodologies, varied timeframes and scales of complexity in traditional multidisciplinary, interdisciplinary and multisectorial models in *CP*, *HECP* and *BRBT* research. Lastly, the article evaluates the singular characteristics of new collaboration structures in *TIBS*, inquiring into its transdisciplinary bearing. This discussion addresses alternative *TIBS* research methods (variable-oriented and process-oriented combinations), and new scalar and timeframe boundaries, evaluating its transformative force for innovation. Distinguishing research boundaries clarifies how technological innovation is produced and introduced. More importantly, it contributes to understanding innovation as the formation of new habits of thought.

Collaboration models and building technology research cultures

Research patterns within construction tend to exhibit defined and highly distinctive collaboration structures.[9] Partnerships are seldom long-term, and are often characterised by a team structure of independent organisations. Hence, the learning process of negotiation and solidification of varying perspectives, research methods and validation is usually disrupted by the fact that each professional and/or organisation has its own independent goals.[10] As such, while the established working practices found within architecture are often inherently multidisciplinary, these traditional collaborations recurrently work in a compartmentalised way and frequently do not have shared goals. However, recent research collaborations with natural science disciplines that are traditionally seen as distant to architecture (for example, material science) have demonstrated successfully that collaboration can become the enabler of creativity and innovation. These new approaches are augmenting the complexity of already intricate collaboration structures in construction. As researchers from these disciplines converge in pursuit of building technology innovation, interrogations of the nature of research and innovation systems arise in this potential new frontier.

1 *a* Diagram of Architectural (Building Technology & Systems) Collaborations: Typical Multidisciplinary collaboration model (compartmentalised) in CP and HECP (partially adapted by author from: <http://ced.berkeley.edu/frameworks/2011/active-matter-matters/> [accessed on 27 July 2013]) *b* Diagram of Architectural (Building Technology & Systems) Collaborations: Interdisciplinary collaboration model in *CP* and *HECP* with BIM integration



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Building technology and innovation in architectural commercial practice

Architects are widely acknowledged as sources of innovation, particularly during early project conceptualisation. However, the perception in wider society is that they neither partake in nor contribute to construction innovation unless strong collaborations across all stakeholders exist.[11] Typically, R&D of a given building technology occurs far from the designer in an industry lab. Since the consolidation of the industry lab in the early twentieth century, building component innovation has been primarily established by major companies such as Pilkington, Corning, DuPont, etc.[12] Architects are often viewed as the adopters or integrators of new technology and systems, with exceptions for 'high-end critical practice' in specific firms, in 'basic research' collaborations in academia, or more recently in 'basic research and fundamental science' research.

In the last decades, research has identified the acceptance of innovation as an improvement in design or construction processes, as well as recognising the importance of evaluating post-occupancy performance by the construction industry.[13] New ideas and problem-solving in construction provides an alternative model to the typical R&D process.[14] Graham Winch describes this as a top-down moment of adoption/implementation and a bottom-up moment of solving/learning.[15] In this system, Winch argues, new ideas can both be adopted by firms and implemented on projects, or result from problem solving on projects which are learned. However, it can be easily argued that the top-down moment would correspond to adopting innovation, not generating it. What role do collaboration structures within commercial practices play in the generation of innovation?

Literature summarises architectural collaboration into four fundamental features: a) creative collaboration usually occurs in predesign, schematic design and design development phases rather than in construction documentation and construction phases; b) during these phases, architects collaborate with clients and consultants rather than with other architects; c) during these phases clients and collaborators bring improvisational suggestions and feedback; and d) representation plays a key role in creative collaboration across these phases.[16] These characteristics represent a rather typical compartmentalised model. In this structure, a typical design tends to be developed through satellite-like input. This method favours either improvisational or afterthought information which is often one directional, and where collaborations from other disciplines are often compartmentalised *[1a]*. Multiple efforts have been made to overcome this type of segregated collaboration.

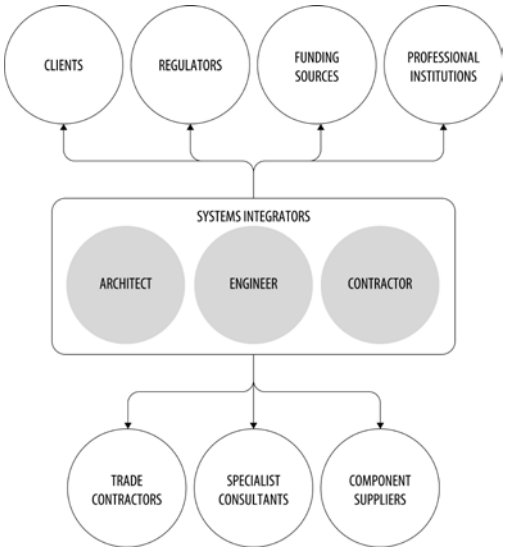
Presently, innovation is primarily understood in *commercial practice* as a means to accelerate the construction timeline and decrease costs without sacrificing design quality. Many architectural practices seek to achieve this through building information modelling (BIM). In BIM, all data associated with a building model can be held in one repository. Its aim is to facilitate the exchange between various domains in the architecture, engineering and construction (AEC) industries through a centralised model. As industry strives to optimise the design process, BIM has become exponentially more prevalent.[17] A survey developed by McGraw Hill determined that in 2012, 71% of architects, engineers, contractors and owners became engaged with BIM. This presented a 75% growth in a five-year span. The survey presented that contractors led the adoption at 74%, with architects and engineers at 70% and 67%, respectively. The surge in adoption points towards dramatic near-future changes in adoption of BIM in the design process.[18]

While it can be argued that BIM has in practice been used for mere visualisation or commercial efficiency (for example, accelerating the design development phase), this view would be reductive. If BIM is understood less as a tool or software, but rather as an integrative design approach, then it is and has been transformational as a collaborative method *[1b]*. BIM's intellectual basis rests on the information processing model of design, and disciplines in computer science (for example, database management), artificial intelligence and computer graphics. It is therefore a unique precedent for collaborations between architecture, engineering and science.[19] Whether BIM acts as a significant enabler of collaboration (*vis-à-vis* mere production) ultimately depends on the social transformations created by the synergistic intersection of a given culture, business model and the technological shifts it affords. When BIM is implemented with a focus on people and collaborative strategies, the value is far beyond a mere software tool for higher time and cost efficiency.[20] The early phase of information models and the innovations fuelled later by BIM in architectural practices have spurred social transformations in collaboration processes including partnerships with academia.[21] These transformations to some extent contribute to a foundation for emerging collaboration between scientists, architects and engineers. Nevertheless, while some transformations are challenging traditional models in commercial practice, industry still operates largely via fragmented project coalitions where architects adopt, rather than create, building technology innovation.

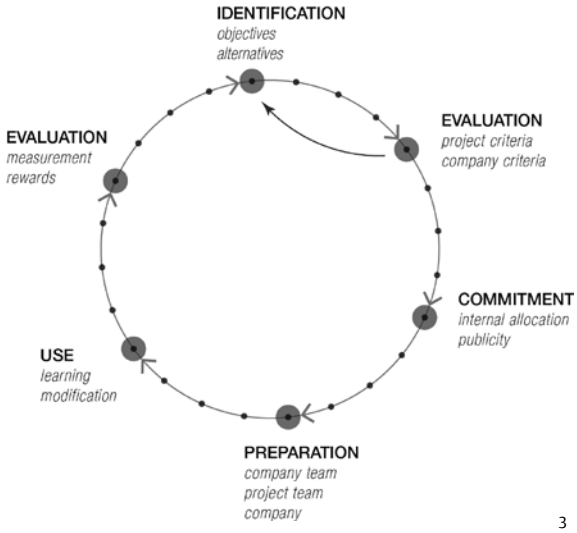
Building technology and innovation in the construction sector

Innovation can come from varying sources within industry, academia and practice. Yet, the role of each component of the chain in a client-driven industry is widely diverse and typically bears a significantly different impact. E. Sarah Slaughter argues that there is stronger potential for successful implementation when innovation stems from sources with knowledge and control over the connections among the components and

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2 Diagram of Innovation in Construction Systems: Integrators as a Complex Systems Industry (with permission, based on Winch, 1998)



3 Diagram of Implementation Stages for Innovation in Construction: identification, evaluation, commitment, preparation, actual use and post-evaluation (with permission, based on Slaughter, 2000)

systems of a chain of action.[22] Unlike many other industries, innovation in construction is typically not implemented within the firm itself but rather in particular projects. In this process, almost all innovations have to be negotiated with one or more actors within the project coalition. As presented in *[2]*, the ultimate ability for a firm or equivalent to produce innovation depends on its role within the 'innovation superstructure' as understood in a complex systems industry.[23] If innovation in construction is understood as structured through a complex systems industry, the system integrator role is typically shared between the principal architect/engineer and the principal contractor.[24] The typical temporary partnerships between the 'system integrators' presented by Winch often lack a shared vision-goal towards innovation, which leads to fragmented collaborations.

Slaughter has summarised the process of construction innovation into six phases *[2]*.[25] This cycle shapes innovations that are incremental, modular, systemic and radical.[26] Slaughter defines these six phases as identification, evaluation, commitment, preparation, actual use and post-evaluation *[3]* with each providing a particular contribution to the innovation cycle. These levels depend both on internal structures and external processes to develop not only novel building technology, but also to generate new knowledge. Data collected through the post-evaluation phase can typically be classified into criteria covering technical, project, organisational and strategic factors, as well as an assessment of wider societal benefits. Taken together these enable a revaluation of the initial criteria that originally influenced the innovation process.

Innovation barriers in construction

Existing literature addresses extensively the inherited and continuing barriers to technological innovation within the construction sector. These can be summarised as: the limited and temporary frameworks for collaboration in design and related practices, a paucity of implementation strategies and a lack of economic incentives. In large part these barriers stem from the particular characteristics of the construction sector with regards to other industries, especially manufacturing. Further, the nature of the final product within the construction sector has been widely characterised by its uniqueness, immobility and variety.[27] Ivory argues that the output in construction is formed as a project production. It can, therefore, be adapted to the buyer, location and use. As a system, the output does not recommend the use of specialised assets for each project. Rather, it requires that the productive assets move to the location of the product placing the economic relevance of each unit of product as a singular output.[28]

The rates of productivity in the EU and US have been presented as significantly lower than in other sectors.[29] Winch asserts that the construction sector does not lack the genesis of new ideas but rather that the rate of innovation lags behind most other industries. The sector is characterised by a disproportional focus on product enhancement rather than process improvement.[30] Hence, Winch argues that the complex products systems model is much more suitable for the construction sector than the predominant Schumpeterian model.[31] His argument is rooted in the notion that complex product systems offer suitable singular characteristics. These are: interconnected and customised elements organised in hierarchies; non-linear and emerging properties; and a high degree of user involvement. In this process, the distinctive contractual relationships of construction are primordial.

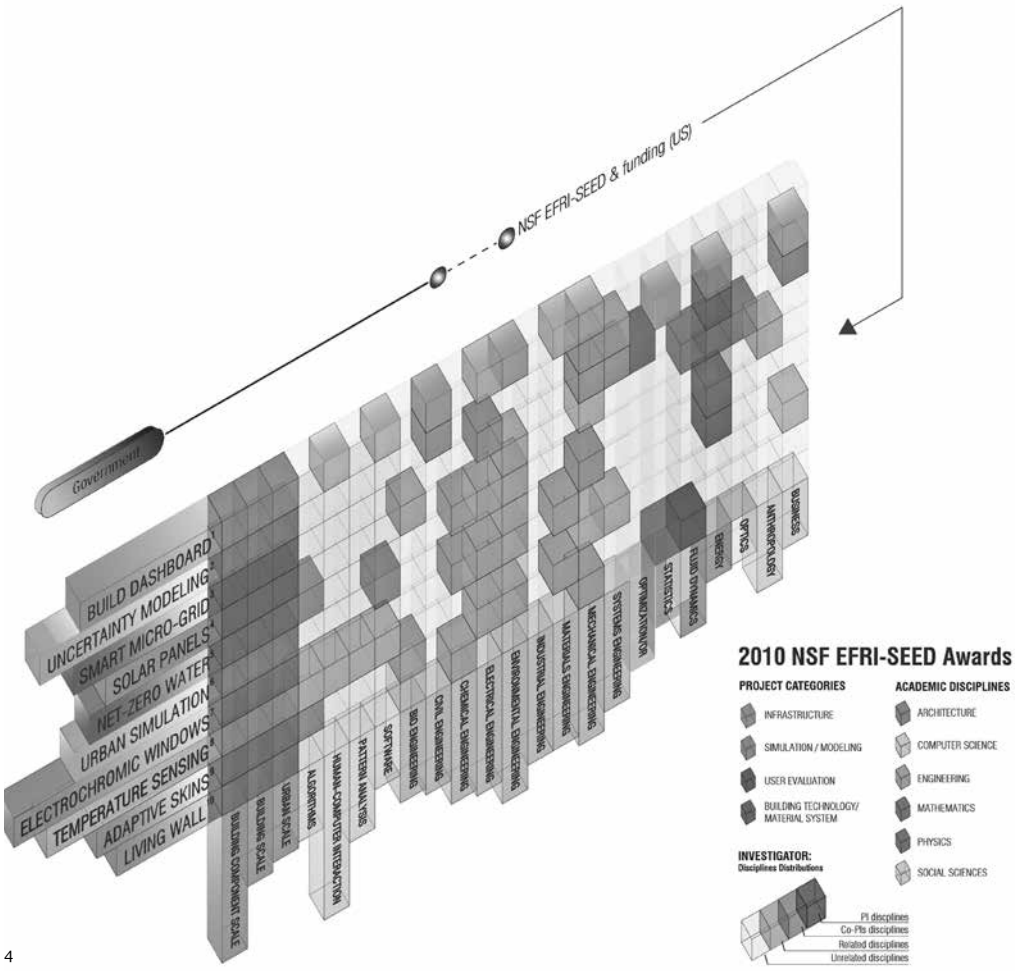
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Innovation structures and contractual relationships

As we move down the construction supply chain to contractors, architects and engineers, we often find a one-to-one service with the client. Winch states that architects and engineers at this level act as 'honest brokers' of technologies for clients.[32] Accompanying this marketing is the 'brokering of technologies from consultants to clients' where consultants also sell the idea of innovative design to clients.[33] To understand the multifaceted factors behind the innovation inertia of the construction sector, the complex multi-actor activity at the project level must be addressed in addition to its intricate output and contractual characteristics. Chris Ivory defines construction innovation as a 'highly political' activity which demands careful and subtle management.[34] In the present regulatory context, clients do not always support innovation. Often clients cannot or will not take the risk in cost, time and/or performance. In a client-run industry, this creates serious challenges.[35] Ivory advocates a dual output system: one to clients in the form of a building and associated services and another to industry in the form of innovation and learning opportunities. However, this view still leaves unclear as to which economic incentives would drive industry innovation. Furthermore, it misses a third model where all stakeholders in the process of construction can be part of the research network. The typical contractual relationships and output characteristics of the construction sector have an impact on opportunities for robust collaboration. Ive identifies the absence of three critical elements – means, motive and opportunity – in one single player as a barrier for incentivising innovation.[36] Furthermore, the absence of market-driven incentives and typical risk-free attitudes towards innovation derive from multiple reasons including liability.[37] All these factors combine to hinder the formation of shared goals critical to generating innovation.

Funding models

Winch argues that funding agencies (for example, Research Councils in the UK, the USA's National Science Foundation) have played an important role in brokering innovation in construction by acting as 'regulatory systems' to fill gaps within the 'systems integrators' model.[38] Figure *[4]* presents the recent EFRI-SEED award by the National Science Foundation which exemplifies the role that funding programmes play to foster opportunities for collaboration at the inception of research and design, geared specifically towards innovation in architecture and fundamental science. Alternative models exist where innovation stems from a shared goal between academia and industry with government intervention (for example, the Fraunhofer Institute's innovation clusters).[39] These regional partnership clusters aim to forge innovation by fostering the nexus between industry and academia through shared goals of both sectors.



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4 Diagram of Research Funding (Sustainable Buildings): Case Study 2010 National Science Foundation's EFRI SEED awards. These projects illustrate the interdisciplinary nature of the research made possible through this new funding model of four years duration

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Building technology research and innovation in high-end critical practice

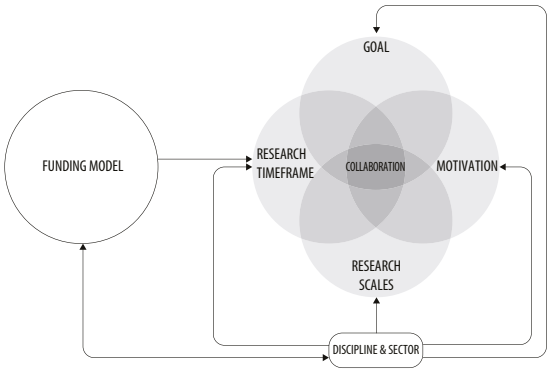
During the twentieth century, solid and successful collaborations between architects and engineers were crucial for building technology progress. From Abba Tor's partnerships with Eero Saarinen to Louis Kahn with Philip Roche and to Oscar Niemeyer with Joaquim Cardozo, these robust collaborations stand as testimonies of how interdisciplinary intersections of architecture and engineering, when non-compartmentalised, fuel creativity and innovation.[40] Jean Prouvé's workshop is a critical example of how building technology innovation has benefited strongly from interdisciplinary collaborations.[41] The sociocultural and industrial transformations taking place within the practice and ethos of architecture at the time supported the robust collaboration of artists, engineers, artisans and architects in his workshop.[42] The convergence of these factors streamlined the transformative force of this interdisciplinary model. In many ways, this example served as a model for many future interdisciplinary workshops in practice that have been crucibles for building technology innovation. In *An Engineer Imagines*, Peter Rice outlines his own collaboration experiences with clients, architects (such as Renzo Piano) and critics, and evaluates the role of these processes in the formation of new building technologies.[43] In fact, building technology innovation in *HECP* (for example, Piano's Building Workshop) has been pivotal not only to advance building technology, but through its influence in shaping our understanding of spatial phenomena and programme.[44] In this discussion, firms such as Ove Arup are establishing clusters specifically devoted to speculations around future shifts in built environments, defining areas such as nano and biotechnology as drivers for future building technology and systems.[45] In fact, as discussed in the next section, the incorporation of these fields in building technology is already taking place in academia through multiscale design research where unprecedented interdisciplinary collaborations in architecture with fields such as bioengineering and material science are crystallising.[46]

Interdisciplinary collaborations & building technology in basic research in building technology in academia

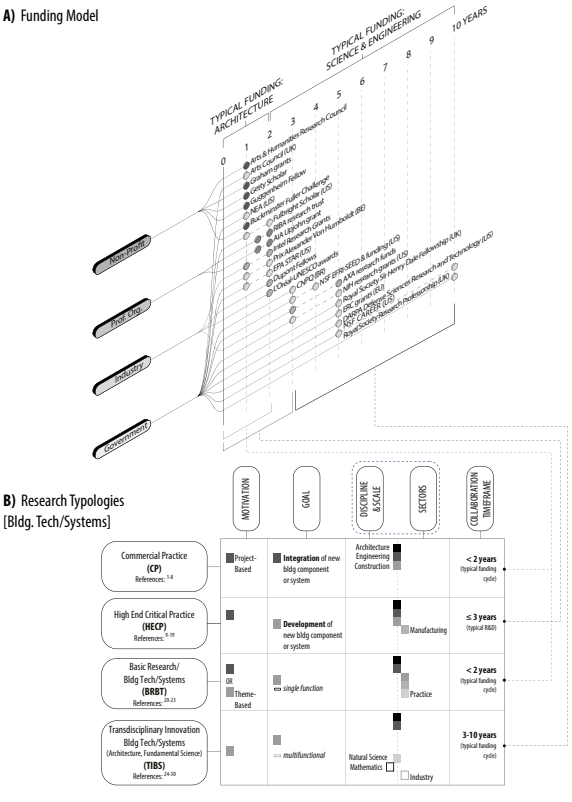
In 1976, the National Science Foundation supported the establishment of the Architectural Research Centers Consortium (ARCC). The enterprise originally involved around thirty schools of architecture across the United States and the research division of the American Institute of Architects.[47] Its initial aim was to serve as a vehicle for communication among researchers through a series of workshops and conferences. These types of research centres promoted discussions around the nature of architectural research, which led to seminal articles and workshops.[48] In the following decades a series of research centres or units were developed within architecture schools specifically devoted towards emerging technologies cross-pollinating building technology and advances in computation.[49] In addition to the recently established programmes with a focus on new technologies and new materials such as the Mediated Matter Group at MIT or The Living Architecture Lab at Columbia, architectural schools are at present housing co-shared programmes and centres geared towards collaborations with practice and/or industry within architecture or interdepartmental clusters (for example, CASE-RPI/SOM; ChangeLabs Stanford). These new clusters are moving towards multisector partnerships that challenge traditional academic collaboration structures in building technology and systems.

Research methods in multidisciplinary and interdisciplinary collaborations in building technology and systems

The conceptual diagram *[5]* illustrates how the formation of a collaboration structure depends on four fundamental factors: motivation, goal, research timeframe and research scale. The research timeframe is largely driven by the funding model



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[6a]. At the same time, this interaction is directly correlated to the disciplinary fields involved in a given research. The convergence of all four factors determines whether the collaborative result is temporary and fragmented, or long-term with shared goals towards innovation that ultimately generates new knowledge.[50] Figure *[6b]* presents a summary of building technology research developed by the four basic clusters: *CP, HECP, BRBT* and *TIBS*. The fundamental difference regarding motivation is whether the partnership is pursued for a project or a research theme, where the former may produce temporary coalitions and fragmented partnerships unless accompanied by a comprehensive implementation and evaluation process.

5 Model of Collaboration Structure: defining agents in Building Technology & Systems Research

6 *a* Diagram of Typical Research Funding Sources and Duration (organised by funding duration) architecture, science and engineering
b Diagram of building technology & systems research clusters: *CP*; *HECP*, *BRBT* and TIBS based on motivation, goal, research timeframe and disciplines involved

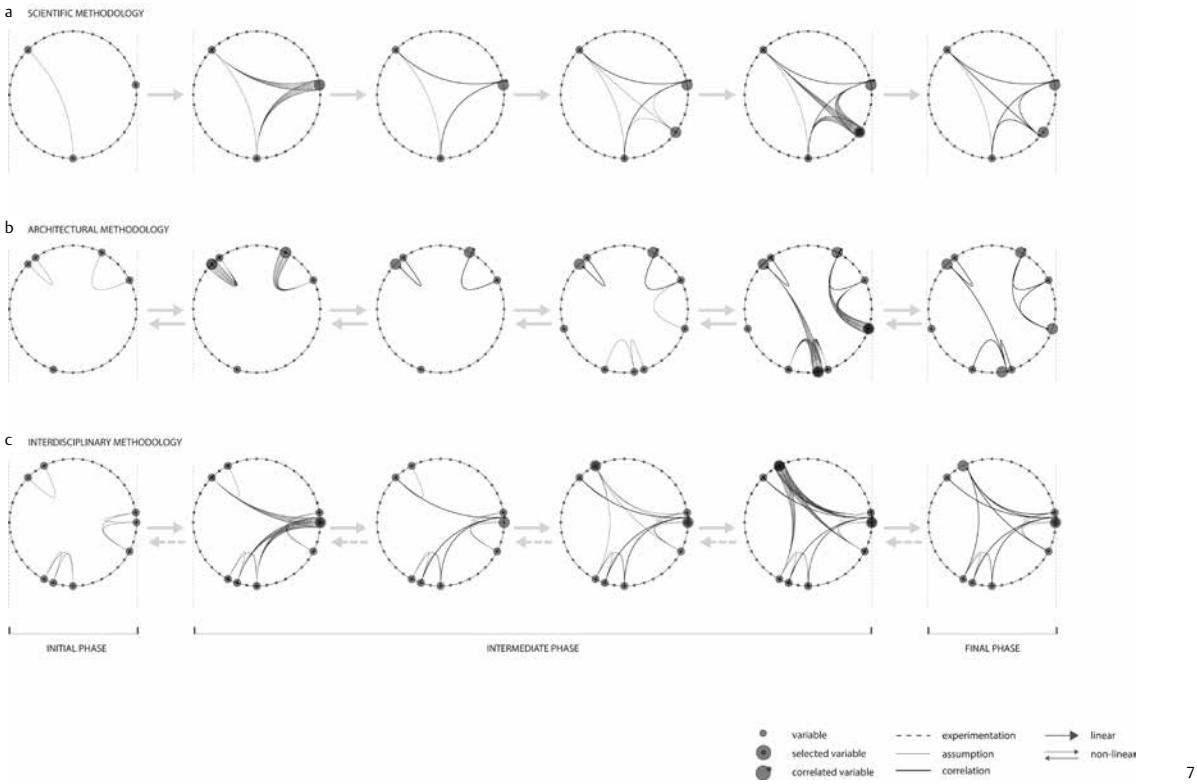
7 *a* Diagram of Building Tech/ Systems Research Variables and Systems Correlation in *HECP* and *BRBT* across project design phases (process-oriented analysis). For architecture, many variables are initially selected. Specific variables may be tested and correlated concurrently but system-wide correlations may not be determined in its entirety
b Diagram of Scientific Research methodologies (variable-oriented analysis). In science, fewer variables are initially selected where one variable is tested while other variables are held constant. Variables are correlated through experimentation and evaluation
c Diagram of Transdisciplinary Research methodologies in *TIBS* (variable and process oriented analysis). As in architecture, more variables are initially selected; as in science, specific variables are selected for testing while others are held constant. Correlations between system variables are determined through experimentation and evaluation in an interdisciplinary manner

Negotiating research methods in *CP*, *HECP* and *BRBT*

Architecture evaluates information differently to science and engineering. Its research methods include many inquiry systems and standards that swivel from design problem formulation to solution. From its origins, building has been acknowledged as concerned with intuitive decisions or rationalised deliberations.[51] Whether through intuitive and/or rational approaches, architecture has been, and always will be, designed through a complex network of measurable and numerically unquantifiable conditions.[52]

With varying views around how creativity and design spur innovation, theoreticians tend to agree that architectural research is interdisciplinary.[53] In the case of building technology and systems innovation, the application of this interdisciplinary lens depends largely on the motivations and goals that drive the research and the structure that supports it. However, while these structures, motivations and goals differ greatly in *CP*, *HECP* and *BRBT*, the research methodology itself may not. The fundamental differences between architectural research and the classic steps of scientific method are often camouflaged by our growing abilities to map and graph data in architecture. This occurs, for instance, through the use of programmes found typically in science (for example, CFD; daylighting simulation). The differences by which we conceptualise a problem and design an experiment, however, remain more evident. This is clearly seen in how we define and correlate independent and dependent variables throughout a given experiment.

Variables and experiment: Architectural research from a variable-oriented perspective can be



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summarised according to three conditions across the initiation, development and conclusion of research. During the initial phase, architectural research typically involves the selection of multiple variables *[7a – left]*. Throughout the development phase, specific variables are tested and correlated concurrently, usually in a non-linear fashion *[7a – middle]*. The research is not structured through incremental variations. While experiments are iterative, they do not follow a specific line of testing based on system-wide correlations where an independent variable is singled out in each iteration. Lastly, the process does not conclude in a system-wide correlation *[7a – right]*. The non-linear and multi-variable procedure of architectural research can be attributed to the fact that architects address multiple subjects (for example, context and experience) and scales, investigated as independent conditions. Architects do not focus on reducing the number of variables during design. Rather than working through a variable-oriented approach, architects function in a more process-oriented manner. This is hardly surprising since design is inherently projective.

Validation: Unlike building science research, investigation in building technology and systems has traditionally not been structured around the scientific method. Unless *BRBT* is directly tied to building science research, the scientific method is not the exclusive or primary canon of performance innovation. The success of a given innovation is often measured by other standards such as decrease in labour. In architecture as a whole, validation also steps far beyond one canon. Yvonna Lincoln and Egon Guba described 'negotiated outcomes' as a form of peer review.[54] Curated exhibitions, competitions and publications all fit into the architectural peer-review fabric and these are supported by quite varied evaluation standards. Unlike engineering or science, there is no universal peer-review validation system in architecture. The research differences between architecture, engineering and natural sciences traverse all research spheres ranging from conceptualisation and experimentation, to validation perspectives.

Research methods in engineering and natural sciences

Variables: As mentioned above, the fundamental differences between architectural and scientific research span from conceptualisation to validation. During initial research, a typical scientific experiment is structured around a minimisation of variables *[7b – left]*. In the scientific method the variable is, as the term implies, the one feature that is modified in an experiment and evaluated regarding how it affects the results. Variables (independent) are changed one at a time *[7b – middle]*. This independent variable is not affected by others. Conversely, dependent variables are those affected directly by changes made to the independent variable. Typically, the scientific method concludes with a system-wide correlation of all initial variables *[7b – right]*.

The traditional research approach has been widely criticised because of its reductive, variable-centred method and its infallible universality to studying any given situation or problem.[55] Joseph Maxwell argues that the overvalued variable-oriented approach to research, typically applied in the natural sciences, tends to deny the possibility of observing causalities in single cases and frequently neglects the relevance of context (an essential component of causal explanation).[56] Moreover, Maxwell argues that variable-oriented research treats qualitative methods as descriptive and supplementary to quantitative methods. These assertions are particularly relevant for social sciences.

Validation: The scientific community presently concurs that an acceptable publication must be the first disclosure that contains clear and sufficient information to enable peers to consecutively assess observations, repeat experiments and evaluate intellectual processes.[57] Since 1972, along with the American National Standard for the preparation of scientific papers for written or oral presentation, IMRAD (Introduction, Methods, Results and Discussion) has been the official standard for journal publication.[58] Peer review functions as a formal validation, both within and outside the scientific community. External peer review broadens the scope of available expertise, especially with the increasing proportion of multi-authored, multidisciplinary works. Over time this method has improved manuscript quality.[59] IMRAD became the canon for disseminating research structured as discussed around a variable-oriented approach. This has served well for scientific experimentation. However, the belief in an exclusively variable-oriented approach in scientific experimentation is proving questionable.

Incentives for transdisciplinary research: The arguable applicability of a single scientific research method for addressing all complex layers of sustainability challenges is leading scholars to reassess collaborative models within science and engineering. These interrogations in combination with recent incentives for developing interdisciplinary research in architecture and science are promoting the generation of new research and collaboration models. These could be summarised as: 1) growing appreciation of evidence-based research by the scientific and engineering communities; 2) building technology innovation patents as a design marketing tool; 3) new funding models for interdisciplinary collaborations (sustainable buildings); and 4) advances in multiscale performance simulation. These areas function as research incentives driven by the desire to generate new knowledge as well as market incentives.[60] However, are emerging collaboration models in pursuit of building technology innovation radically new and potentially transformative? Is it the product of transdisciplinary collaborations?

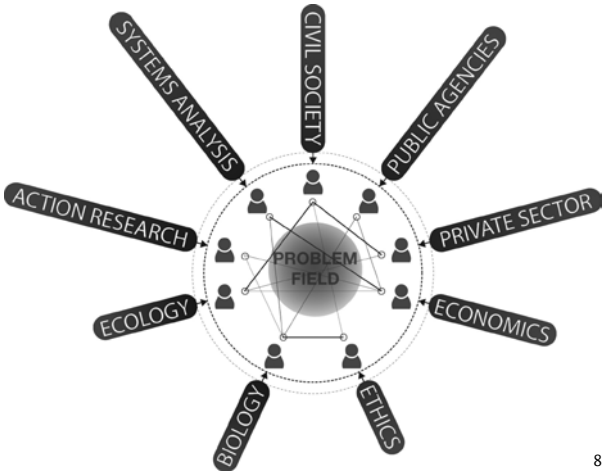
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Shifting towards transdisciplinary innovation of building systems

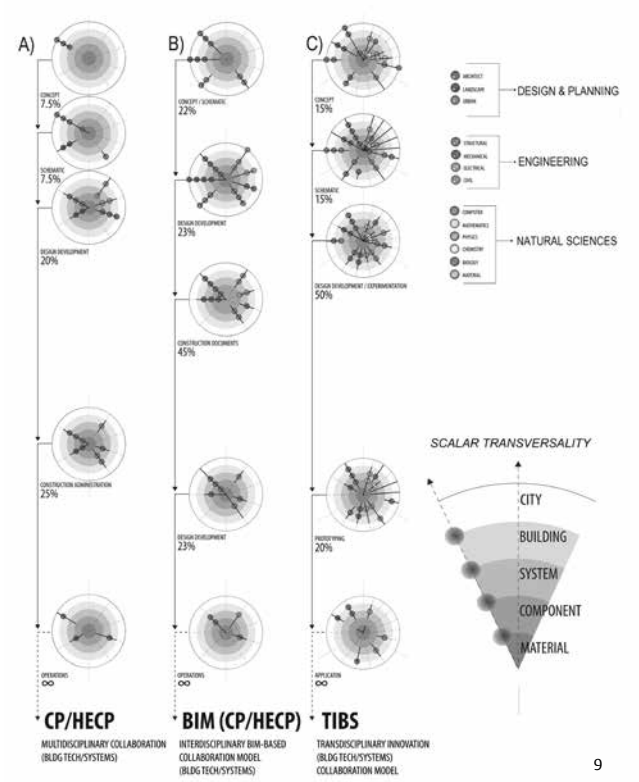
New disciplinary convergences within academia are emerging as interdependent design and research pursuits. These collaborations are not project based but rather theme-oriented, where scholars with common motivations and goals partner to advance multiple disciplines. As such, the studies established by these collaboration networks are geared towards long-term research and partnerships, encompassing multiple scales of investigation from nanoscience to regional analysis. Predominantly, these emerging collaborations are supported by significant government funding which enables architects, engineers and scientists from disciplines such as biology, bioengineering and physics to collaborate through research shared goal(s). Partnerships such as BIOMS/BioPOETS (UC Berkeley), Sabin+Jones/LabStudio (UPenn), and within the Wyss Institute (Harvard) are transforming the development of building enclosures through a multiscale design approach towards material systems.[61] Through these initiatives, scholars confront the difficulty in negotiating diverging research methods and timeframes.

Literature defines transdisciplinary research as identifying, structuring, analysing and addressing issues in fields that bridge basic, pure knowledge with solving societal issues.[62] This is understood as the ability to grasp a problem while taking into account the diversity of real world and scientific perception of problems, and link abstract and case-specific knowledge that promotes the common good.[63] Transdisciplinary research requires social and communication skills to integrate knowledge from different action domains, both within and outside academia constraints.[64] Literature recognises systems, target and transformation knowledge as the three basic types of fundamental knowledge in transdisciplinary collaborations.[65] Systems knowledge is driven by interrogations around the genesis and possible development of a problem and its life-world interpretations. Target knowledge pertains to questions related to determining and explaining the need for change, desired aims and better practices. Lastly, transformation knowledge is structured through questions about technical, social, cultural, legal and other means of action to transform existing practices and introduce new ones.[66] According to this view, transdisciplinary research in architecture must comply with all these forms of knowledge ranging from interrogations of the origin of a problem to transforming existing practices. New disciplinary intersections at the inception of design in pursuit of building systems innovation point towards new approaches of how to frame a design problem, how to drive experiments, and how to evaluate them.

The *TIBS* model encourages maximising system-wide correlations without sacrificing the plurality and multi-variable nature of the interdisciplinary architectural view [7c – left]. This negotiation of maintaining more than a variable at each research



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8 Diagram of Transdisciplinary Collaboration model. In Pohl and Hirsch-Hadorn's transdisciplinary model, different sectors including academia, civil society and the private sector become interrelated and transformed through a problem field

9 *a* Diagram of Research Scales (Building Tech/Systems) across project design phases in *CP* and *HECP*: scalar implications of typical multidisciplinary research models in architecture. Diagram presents a very compartmentalised and restricted network. It also displays a predominantly hierarchical system across design phases *b* Diagram of Research Scales (Building Tech/Systems) across project design phases in *CP* and *HECP* with BIM integration: scalar implications of BIM integration in research structure. Diagram presents a degree of *scalar transversality* and primarily combined degrees of hierarchies across design phases *c* Diagram of Research Scales (Building Systems) across project design phases in *TIBS*: scalar implications of transdisciplinary research models in architecture. Diagram presents a dense *scalar transversality* and lesser hierarchical networks across design phases

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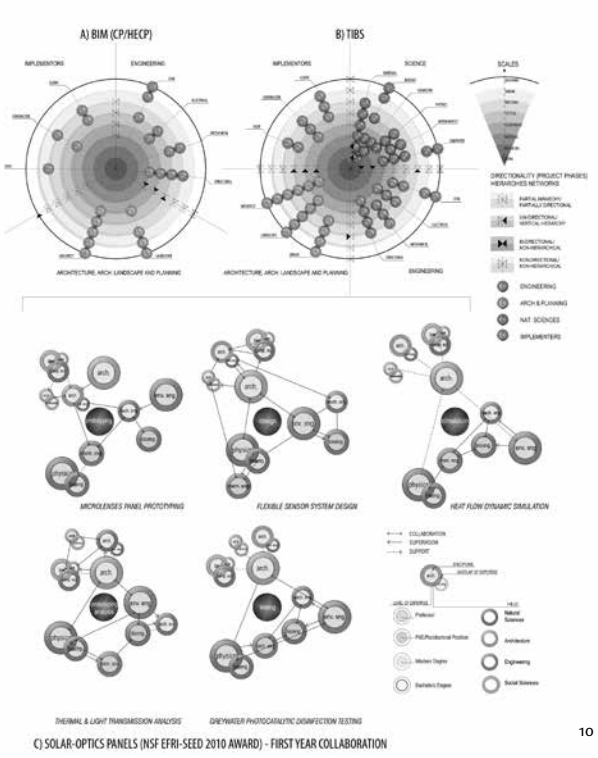
stage while maximising interdependencies inherently defines a less sequential research modality, closer to the non-linear structure of process-oriented architectural research *[7c – middle]*. However, the culmination of research is rather similar to a scientific approach from the perspective that strong system-wide correlations are built *[7c – right]*. Conversely, because it is non-linear and process-oriented, the interdependencies of variables are a lesser degree of direct cause and effect, as expected in design. The counterintuitive interplay of variables in architectural research cannot be overlooked. In process-oriented research conditions do not necessarily follow direct interdependencies of cause and effect (for example, temperature is raised, air is heated). And yet, the way architects approach design is by attempting to evaluate multiple conditions (for example, aesthetic qualities that are dependent on light intensity and reflection) that cannot be directly or exclusively measured in physical units synergistically. The loss of natural philosophy sacrificed a more holistic understanding of nature and artificial phenomena and with it a robust predisposition to an interdisciplinary vision. The convergence of architecture, science and engineering newly reclaims this territory.

The variations of the research scales, timeframes and disciplinary convergences in *CP*, *HECP* and *BRBT* presented in *[9]* are complex. These depend on whether there is implementation of new collaborative platforms such as BIM in *CP* and *HECP,* as well as, if *BRBT* involves multiple sectors from the inception of design. Based on this notion, the following diagram defines three major nexus: a) typical *CP* and *HECP,* b) *CP* and *HECP* with strong BIM integration; and c) *TIBS*. *BRBT*, on the other hand, fluctuates between project-based and theme-based collaboration hierarchies, and has varying funding models. As such, this group can be either clustered with *CP* and *HECP* with strong BIM, or *TIBS* depending on the research scales, timeframes and sectorial/disciplinary hierarchies. For this reason, *BRBT* is not isolated; however, it is important to note that in *[6]* the motivation and goals differ significantly from *CP* and *HECP,* leading ultimately to a different collaboration structure and nature.

Stakeholders in transdisciplinary collaborations

If we adapt Christian Pohl and Gertrude Hirsch Hadorn's transdisciplinary model in sustainable science *[8]* to the specific context of sustainable building technology, we could argue that the practitioner-actors would include not only firms, clients, contractors and users, but also governmental agencies and NGOs involved in multisectorial collaborations. Key sustainable science initiatives in recent years demonstrate this course by streamlining new building technology research models.[67] Fuelled by these new collaborative networks, *TIBS*' transformative potential is beyond the formation of new approaches towards variables and system correlations. It also impinges on the scales implicated in the research of a building system and/or infrastructure.

Research scales in TIBS: Traditionally, architects design at different spans than those involved in engineering and science research *[9]*. Scalar extents in architecture swing from construction to the full building or even urban scale. In traditional architecture collaborations, research does not usually encompass nano and micro scale investigation. As presented in *[9a]*, traditional collaboration is frequently structured through compartmentalised scalar boundaries even when they involve multiple disciplines. These segregated operations are often hierarchical in nature. A key contribution of BIM to *CP* and *HECP* has been incentivising the connection of previously compartmentalised research scales. Through spurring the sharing of information



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10 *a* Diagram of Research Scales (Building Tech/Systems) per field and discipline in *CP* and *HECP* with BIM integration: this model promotes a non-hierarchical interaction between implementers (for example, contractors) and architects or engineers. In practice the collaboration between architects and engineers, while less hierarchical than in typical models, is still predominantly one-directional *b* Diagram of Research Scales (Building Systems) per field and discipline in *TIBS*: research models in TIBS are geared to advance in parallel basic science, fostering a non-hierarchical interaction between scientists, architects and engineers. This structure promotes a multiscale design approach in research which can be seen through a dense *scalar transversality* *c* Case study Diagram of potential *TIBS*: disciplinary networks, hierarchies, and research scales across early design phase. Through a theme-oriented research structure (case study-NSF-EFRI-SEED 2010 award #1038279) disciplines converge in a network that enables horizontal/non-hierarchical collaboration primarily of the principal investigators (for example, architecture, environmental engineering and bioengineering) and directional collaboration of adjacent disciplines to the research (for example, chemical engineering, law, computer science) across each building system research theme

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across disciplines, BIM creates a condition of *scalar transversality* through a stronger interdependency of scales in research in *CP* and *HECP [9b]*.

This distinctive interdisciplinary link across traditionally segregated scales can revolutionise not only a given product (for example, a photoreactive panel), but the way it is conceptualised across various environments (building, neighbourhood, region). *TIBS* capitalises on the ground fertilised by BIM and expands research into a fuller scalar transversality *[9c]*. Likewise, a culture driven towards basic research in *BRBT* has cemented a foundation towards theme-based research with a focus on multifunctional building systems. The emerging research methodologies which combine process-oriented and variable-oriented research *[9c]* are the crucible for this dense scalar transversality. This synergistic research methodology renders *TIBS* potentially transformative.

Research timeframes in TIBS: In *[9]*, we also see the fundamental differences of *TIBS* vis-à-vis BIM in *CP*- and *HECP*-based collaborations across various design phases. BIM-based research in *CP* and *HECP* contributes to a more efficient collaborative design process by bridging research scales in less hierarchical networks. This model provides longer research timeframes in the schematic design phase, promoting conceptual innovation *[8b]* while aiming towards accelerating productivity.[68] However, BIM-based collaborations in *CP* and *HECP* are for the most part still restricted to relatively short time frames as required by the construction sector. Likewise, as presented in *[9]*, typical multidisciplinary collaborations in *CP* and *HECP* are restrained by constricted research time spans during the concept and schematic phase. The longer timeframes of *TIBS* paved initially by *BRBT* across not only conceptual and schematic phase but design development can open opportunities for radical shifts in building technology investigations.

Broadening investigation scales in architecture has an impact not only on the timeframe distributions of a given design process, but also the implicit hierarchies of interdisciplinary collaborations *[10]*. As presented in *[8]* and *[9]*, BIM in *CP*-, *HECP*- and *BRBT*-based research models in architecture does not involve the generation of fundamental science. Consequently, these collaborations have reduced scalar interaction more *[10a]* than *TIBS [10b]*. The BIM model in *CP* and *HECP* encourages a non-hierarchical interaction between implementers (for example, contractors) and architects or engineers. However, the collaboration between architects and engineers, while less hierarchical than in typical models, tends to be one-directional (design) *[10a]*. This implicit condition is not derivative of the affordance of BIM media; rather, it is the consequence of inherited practices in construction.[69] The *BRBT* collaboration models present often similar hierarchies to traditional *CP* and *HECP* despite having substantially different motivations. Conversely, broad scalar span in *TIBS* goes hand-in-hand with non-hierarchical networks. Horizontal collaboration stems from the parallel need to advance building technology and science requiring a more fluid exchange from the inception of design.

In *[10c]*, we see how horizontal networks develop across a representative case study of EFRI-SEED award. In this investigation, the resulting network displays both horizontal and directional collaborations. In parallel, hierarchical collaborations result from interaction between the principal investigators and adjacent or supporting disciplines. The resulting networks vary not based on scale or variable *per se*, but rather on research themes defining the hierarchies within the network.

TIBS requires a multiscale design structure to conceptualise and develop a design pursuit. *TIBS*, however, does not inherently promote a horizontal network with implementers. Unless *TIBS* is structured around strong multisectorial collaborations, as proposed by Pohl and Hirsch Hadorn's model, it will not be fully transformative since implementers are not directly involved. Human and social networks are fundamental to advance user-inspired research. Nonetheless, the rise of new funding programmes is pivotal for transdisciplinary models in building systems research. If nothing else, more time enables more opportunities to communicate and negotiate investigation methods and perspectives. Transdisciplinary research can shift not only investigation patterns, but our perception of innovation.

Conclusion

Since the second half of the twentieth century, large industries have been the primary developers of material and technological innovation of high-performance building systems.[70] These technological advances have taken place far from the construction site. With the exception of privately sponsored research in firms with internal clusters devoted to innovation which constitute high-end critical practice, major government research laboratories and in basic research in academia, architects have not been directly involved in building technology and systems innovation. For the most part, architects have been adopters of new technologies. Traditional collaboration models in commercial practice and even in high-end critical practice are proving to be either unsuitable or insufficient for a radical innovation of building technology increasingly more relevant for sustainable/high-performance aims. Advances in social transformations in collaboration structures through platforms such as BIM in commercial practice and high-end critical practice, and previous research models in basic research have paved the way towards new opportunities to bridge scalar and epistemological gaps. This basis serves to solidify non-hierarchical structures where science, architecture and engineering converge at the inception of design. As structures with shared motivation and goals as well as theme-oriented investigations can be potentially transformative by

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challenging how innovation is conceptualised and produced in building technology.

Through shared knowledge and non-hierarchical approaches this emerging collaboration model ignites new research methodologies and scales of investigation supported by longer timeframes and stronger funding. Consequently, they can shape transdisciplinary innovations in building technology and systems [*TIBS*]. This model enables an integrative research method where, without sacrificing an interdisciplinary architectural vision, variables are explored through stronger system-wide correlations. Conversely, scientists and engineers are exposed to alternative research models spanning beyond an exclusively variable-oriented approach. Through this negotiation process, *TIBS* advances stronger links across scales. The research model fosters denser *scalar transversality* which in turn strengthens non-hierarchical collaborations, supplanting the predominantly compartmentalised operations in restricted fields (for example, building components segregated from urban conditions), and reclaims an integrated view of the built environment without sacrificing disciplinary expertise. If partial hierarchies emerge in *TIBS*, these are consequent to the problem field rather than to a given discipline superseding another by pre-configuration.

With the will to embrace scientific research through interdisciplinary collaborations come not only difficulties in collaboration but the need to re-evaluate our own value perspectives. Concurrent to the proclivity to embrace interdisciplinary research in design innovation in the built environment, literature also discusses the need to critically evaluate how we negotiate and relate to values, perspectives and even methods in the sciences as we exercise design.[71] Peeling off the complex layers of prospective research transformations is critical to architects; it contributes to understanding the very nature of design invention. Extended research timeframes, integrated scales of investigation and negotiated perspectives around construction systems support a potential paradigm shift. The transformative force involved in reinventing how building systems are conceptualised and materialised is not simply technological improvement. The reinvention of conceptual frameworks and processes of technologies becomes transformative when it situates itself beyond the introduction of new productions. Transdisciplinary research in building technology can craft new habits of thought; it reorients innovation.

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