On the Adoption of Computing and IT by Industry: The Case for Integration in Early Building Design

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Abstract. Civil engineers were among the first professionals to embrace computerization more than 50 years ago. However computing applications in construction have been in general unevenly distributed across the industry. The significance of such a situation cannot be overstated, particularly in the North American context where fragmentation plagues the structure and the mode of operation of the industry. The paper attempts first to characterize the adoption of computing and IT tools by the industry, to describe the current status of this penetration as well as factors that prevent the practice from embracing the new technologies. Integrative approaches may hold the key to the development of a new generation of computing and IT tools that counteract effectively fragmentation in the industry. An on-going research project is briefly described to illustrate recent developments in the area of collaborative work and integration across disciplines for the conceptual design of building structures.

1 Introduction

Undoubtedly, professionals in the AEC industry (architecture, engineering, construction) are now routinely using computing and IT tools in many tasks. While this situation would indicate that the industry is keeping up with technological developments, a quick comparison with other industries such as automotive or aerospace reveals that computing applications in construction have been sporadic and unevenly distributed across the industry, with a major impact only on a few tasks/sectors. The significance of such a situation on the construction industry in North America cannot be overstated. It has resulted in a loss of opportunities, indeed competitiveness on domestic and foreign markets, and a level of productivity that lags behind that of other industries. Even among researchers and reflecting on the past 20 years of conferences about computing in construction, one can easily note a progressive “lack of enthusiasm” for computing research over the last few years, to the point where the frequency and size of annual events have been questioned (particularly true for ASCE-TCCIP, American Society of Civil Engineers – Technical Council on Computing and Information Technology).

This paper will first attempt to understand better the current status of IT use and developments in the AEC industry as well as the main roadblocks for widespread adoption of better tools and solutions by practitioners that should inform our collective R&D agenda. A research project will also be presented briefly to illustrate innovative ways of advancing integration in building design.

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2 Computing and IT Use in AEC Industry

Civil engineers were among the first professionals to embrace computerization more than 50 years ago. Early prototype applications were rapidly developed for highly structured numerical tasks like bookkeeping, surveying and structural analysis. The adoption of computer-based solutions however entailed a significant level of investments in highly specialized resources – computer-literate technical staff, costly hardware, complex and unwieldy software – that only few organisations could afford like academia, some governmental services and large consulting firms. The availability of microcomputers in the early ‘80s signalled a turning point in the development, and subsequent adoption, of computer-based solutions by the majority of AEC firms. Twenty years later, one can argue that the majority of structured, single tasks have been successfully computerized and marketed to practitioners in the construction industry [1]. With the advent of new technologies like RFID, wireless, Bluetooth, GPS, internet-based services etc., computer-based solutions and tools appear to be accessible to all, mobile as well as ubiquitous.

Given the availability of such solutions, what can be said of their actual use and adoption by the AEC industry ? Three studies have been conducted in Canada in an attempt to answer these questions. On the current and planned use of IT and its impact on the industry, a survey by Rivard [2] in 2000 found that many business processes were almost completely computerized and the tendency was toward a greater computerization of the remaining processes. IT also raised productivity in most business processes and resulted in an increase in the quality of documents and in the speed of work, better communications, simpler and faster access to common data as well as a decrease in the number of mistakes in documentation. However, the benefits of IT came at a cost since the complexity of work, the administrative needs, the proportion of new operations and the costs of doing business all increased. Furthermore, although the Internet was adopted by most firms surveyed, design information was still exchanged in the traditional form. The two research topics that were clearly identified as the most important by industry were computer-integrated construction and better support for concurrent and conceptual design.

A second and related study in 2004 reported on eleven case studies from across Canada to define an initial compendium of Best Practice in the use of IT in construction [3]. The professionals interviewed included architects, engineers, general contactors and owners at the cutting edge in the use of IT. The documentation of their pioneering use of IT demonstrated how useful these technologies can be and what potential pitfalls are of concern. The following technologies were demonstrated : 3D CAD, commercial Web portals, and in-house software development. However, such a select group of professionals also pointed to a number of pragmatic issues that can impede significantly the use of IT in construction : a) the speed at which projects progress, b) money (always !), c) the difficulty of introducing a new CAD system, d) the cost to maintain trained personnel, e) the difficulty to champion IT when collaborators lag behind (e.g. small contactors), f) the necessity to maintain some paper work, and finally g) the implementation of an information system which has to focus on the construction process, i.e. on the work culture rather than on the technology.

Computing and information technologies can affect profoundly how information is generated and exchanged among collaborators in an industry that is highly fragmented as the AEC in North America. A third study was carried out recently among various stakeholders in construction projects to better understand the impact of information exchange and management [4]. The preliminary results indicate that people in construction prefer traditional, low-tech communication modalities. Table 1 shows to what extent each technology or communication mode is used by participants and how they perceive that such technology makes them more efficient. E-mails, with or without attached documents, is the most frequently used method of communication, followed by phone calls and face-to-face meetings. Similarly these methods of communications are perceived to contribute to personal efficiency. At the other end of the spectrum, groupware, planners with cell phone capacity, walkie-talkie type cell phones and chat appear to not be used frequently. Research participants also do not perceive these IT to contribute to their efficiency. Hence, there is consistency between IT usage and perceived contribution to personal efficiency for high and low frequency of IT usage. Documents obtained on FTP sites and regular cell phones are not contributing either to higher efficiency. In terms of which technology or communication mode was considered the most (or the second most) efficient as a

Table 1. Technology or communication mode. Frequency of usage and perceived efficiency (M: mean, SD: standard deviation).

a) Frequency of usage

	IT usage	
Technology or communication mode	***M***	***SD***
Email without attached document	4.58	0.64
Email with attached document	4.54	0.58
Phone with one colleague	4.50	0.65
Face-to-face meetings	4.35	0.63
Fax	4.12	0.86
Regular cell phone	3.58	1.27
Private courier	3.42	0.90
Electronic planner without cell phone capacity	2.85	1.29
Phone or video conferencing	2.75	0.53
Document obtained from an FTP site	2.72	0.89
Portable computer on construction site	2.58	1.10
Pager	2.31	0.84
Chat	2.29	1.04
Walkie-talkie type cell phone	2.28	1.10
Electronic planner with cell phone capacity	2.24	1.09
Document obtained from web portal	2.17	0.95
Groupware	2.00	1.08
Note: Scale for frequency: 1=unknown technology, 2=never, 3=sometimes, 4=often, 5=very often.		

b) Perceived efficiency

	Perceived efficiency because of IT usage	
Technology or communication mode	***M***	***SD***
Email with attached document	4.80	0.58
Face-to-face meetings	4.76	0.52
Email without attached document	4.76	0.52
Phone with one colleague	4.72	0.61
Fax	4.44	0.65
Private courier	4.12	1.01
Document obtained from an FTP site	3.78	1.54
Regular cell phone	3.64	1.66
Phone or video conferencing	3.33	1.55
Electronic planner without cell phone capacity	2.61	1.83
Document obtained from web portal	2.42	1.77
Portable computer on construction site	2.39	1.67
Chat	1.75	1.26
Walkie-talkie type cell phone	1.70	1.40
Groupware	1.68	1.29
Electronic planner with cell phone capacity	1.67	1.34
Pager	1.65	1.19
Note: Scale for efficiency: 1=does not apply, 2=strongly disagree, 3=somewhat disagree, 4=somewhat agree, 5=strongly agree.		

function of key stakeholder, results clearly show that the telephone is the method of choice. Overall, participants favored using the phone individually to communicate with internal team members (69 %), with internal stakeholders (73 %), with clients (54 %), with professionals (62 %), with general contactors (50 %), and with higher management (58 %). With respect to which technology or communication mode was considered the most (or the second most) efficient as a function of project phase, results are also quite clear. Participants favored face-to-face meetings to communicate during the feasibility study (50 %), during construction design (46 %), during construction to coordinate clients, professionals and contractors (50 %), during construction to manage contactors and suppliers (54 %), commissioning (46 %), and during project close-out (39 %). Hence, participants clearly favoured traditional communication modalities such as the phone or face-to-face meetings, irrespective of project phase and internal or external stakeholders.

3 Impediments to Wider Use of Computing and IT

It is well known that the AEC industry represents a major segment of national economy, accounts for a significant proportion of the gross domestic product and the total workforce, yet lags behind other industrial sectors in terms of productivity, innovation and competitiveness, especially in the North American context. The deeply fragmented structure and mode of operation of the construction industry are to be blamed for such a situation. The implementation of integrative solutions throughout the entire building delivery process, i.e. among various people and products involved from project inception until demolition, would appear as key to counteract such fragmentation, with the adoption of computing and IT by the industry playing a capital role in facilitating the development of such integrated solutions. The aforementioned studies reveal a contradiction in the adoption of new technologies: on the one hand, computerization and IT can now be relied upon in many tasks performed by the majority of stakeholders in the AEC industry, yet on the other hand, promises brought by the new technologies remain unfulfilled, thus leaving practitioners to contend with new complexities, constraints and costs that make them stick with traditional approaches, with the ensuing poor performance. Many factors were pointed out in the above studies as impeding the adoption of computing and IT, and these corroborate the findings of other researchers.

At the 2003 conference of CIB W78 on Information Technology for Construction, Howard identified patterns in the evolution of IT developments over a 20 year-period in six areas as hardware, software, communication, data, process and human change. While he qualified progress in the first three as having surpassed initial expectations, he deplored only slow progress in the remaining areas – the lack of well organized, high quality building data and our inability to change either processes or peoples' attitudes [5]. Whereas CIB reports on the conditions of the construction industry world-wide, the above comments would only be more relevant to the North American context with a profoundly fragmented industry that is incapable of developing a long-term coherent vision of its own development nor to invest modest amounts to fund its own R&D. The few notable exceptions only cater to the R&D needs of their own members, such as FIATECH which groups a number of large capital projects construction/consulting companies in the US. Similarly with reference to computing support in the field of structural engineering, Fenves and Rivard commented on the drastic disparity between two categories of environments, generative (design) systems vs analysis tools, in terms on their impact on the profession. Generative systems produced by academic research have had negligible impact on the profession, unlike analysis tools, possibly because of a lack of stable and robust industrial-strength support environment [6]. One can argue also that engineers worldwide are still educated to view design as a predominantly number-crunching activity, like analysis for which computers represent formidable tools, rather than a judgment-intensive activity relying on qualitative (as well as quantitative) decisions.

In short, computing and IT advances have been numerous and significant in the AEC industry in terms of hardware, software and communications. However the industry remains profoundly divided and under-performing compared to its peers because these technologies are still incapable of accounting properly for human factors like :

- the working culture, style and habits, which ultimately determine the level of acceptation or resistance to change toward new environments ;
- the training needs of individuals who have to feel "at ease" with new technology in order to maintain interest and adopt it on a daily basis ;

- the interdisciplinary nature of communications, decision-making and projects which is poorly captured in automated support environments ;
- the intrinsic complexity and uncertainty of information used at the early stages of project development i.e. at the time when decisions have the greatest impact on the final product performance.

Research agendas for the development of computing and IT tools in construction must address the above human factors in priority if wider acceptance by the practice is pursued. Examples of promising avenues are given elsewhere [7]. As mentioned above, one of the most effective ways to counteract fragmentation in the industry is to promote the development of integrative solutions. In the long-term, integration should be as broad as possible and enable decision-making as early as possible in the process, at a time when decisions have the greatest impact on the overall facility life-cycle performance. This ambitious goal may not be reached for quite a long time yet although numerous IT developments to date have addressed some aspects of integration, like improved communications by means of exchange protocols. This low level of integration was made possible more than 20 years ago by industry-driven exchange protocols like IGES and DXF files for drawings, lately followed by the more general IFC's [8] which are progressively making possible effective communications across firms that are geographically dispersed, even among different disciplines and distinct project phases. However too many tasks in the building delivery process still lack the ability to communicate effectively with each other, by means of IFC's or otherwise i.e. to "interoperate". A recent survey about the situation in the US alone for capital projects evaluates the annual cost of such a lack of interoperability at 15.8 G $ [9].

There are many other characteristics of the construction industry that contribute also to slowing down, even hindering, the penetration of IT and computing in practice. For example, the fact that building projects produce a single unique product, erected once in an unprotected natural environment — unlike mass production in a manufacturing environment — has been discussed and documented for a long time [10], thus does not need repeating here. However what may be useful at this point is the presentation of a research project that attempts to achieve an integrated solution while accounting for some of the aforementioned characteristics. In the next section, the development of an innovative approach that endeavours to advance integration at the early stages of building design is described briefly.

4 Enabling Interactivity in the Conceptual Design of Building Structures

Nowadays, advanced computer modeling tools are available to support structural system generation, analysis, and the integration to the architecture [11]. This kind of support is model-based since it relies on the geometric and data modeling capabilities of a building information model (BIM) that combines the building architecture with other disciplines. Explicit knowledge can be used in conjunction with BIM's in the form of requirements. These requirements constrain the model and maintain its consistency when changes take place. This type of knowledge support could be called passive since it validates or confirms design decisions that have already been made. However, these tools lack the knowledge required to assist the engineer to explore design alternatives and make decisions actively. A knowledge-based approach is proposed that aims at providing interactive support for decision-making to help the engineer in the exploration of design alternatives and efficient generation of structural solutions. With this approach a structural solution is developed by the engineer from an abstract description to a specific one, through the progressive application of knowledge interactively.

Researchers have applied artificial intelligence (AI) techniques to assist engineers in exploring design alternatives over a vast array of possible solutions under constraints. Relevant techniques that have been explored over the last 30 years are: expert systems, formal logic, grammars, case-based reasoning (CBR) systems, evolutionary algorithms and hybrid systems that combine AI techniques such as a CBR system with a genetic algorithm. The impact of AI-based methods in design practice however has been negligible mainly because the proposed systems were standalone with no interactions with design representations currently employed in practice, such as BIM's. In fact, only few of the research projects [12] used architectural models with 3D geometry as input for structural synthesis. In the absence of such models, only global gravity and lateral load transfer solutions could be explored to satisfy overall building characteristics and requirements. These solutions needed actual architectural models to be substantiated and validated. Another disadvantage of the above research systems that hindered their practical use was that the support provided was mainly automatic and the reasoning monotonic (i.e. based on some input, these systems produced output that met specified requirements).

By contrast, a hierarchical decomposition/refinement approach to conceptual design is adopted in this research [13] where different abstraction levels provide the main guidance for knowledge modeling. This approach is based on a top-down process model proposed by Rivard and Fenves [14]. To implement this approach the structural system is described as a hierarchy of entities where abstract functional entities, which are defined first, facilitate the definition of their constituent ones.

Figure 1 illustrates the conceptual structural design process. In Figure 1, activities are shown in rectangles, bold arrows pointing downwards indicate a sequence between activities, arrows pointing upwards indicate backtracking, and two horizontal parallel lines linking two activities indicate that these can be carried out in parallel. For clarity, in Figure 1 courier bold 10 point typeface is used to identify structural entities. As shown in Figure 1, the structural engineer first defines independent structural volumes holding self-contained structural skeletons that are assumed to behave as structural wholes. These volumes are in turn subdivided into smaller sub-volumes called structural zones that are introduced in order to allow definition of structural requirements that correspond to architectural functions (i.e. applied loads, allowed vertical supports and floor spans). Independent structural volumes are also decomposed into three structural subsystems, namely the horizontal, the vertical gravity, and the vertical lateral subsystems (the foundation subsystem is not considered in this research project). Each of these structural subsystems is further refined into structural assemblies (e.g. frame and floor assemblies), which are made out of structural elements and structural connections. The arrangement of structural elements and structural connections makes up the "physical structural system". During activity number 2 in Figure 1 (i.e. Select Structural Subsystems), the engineer

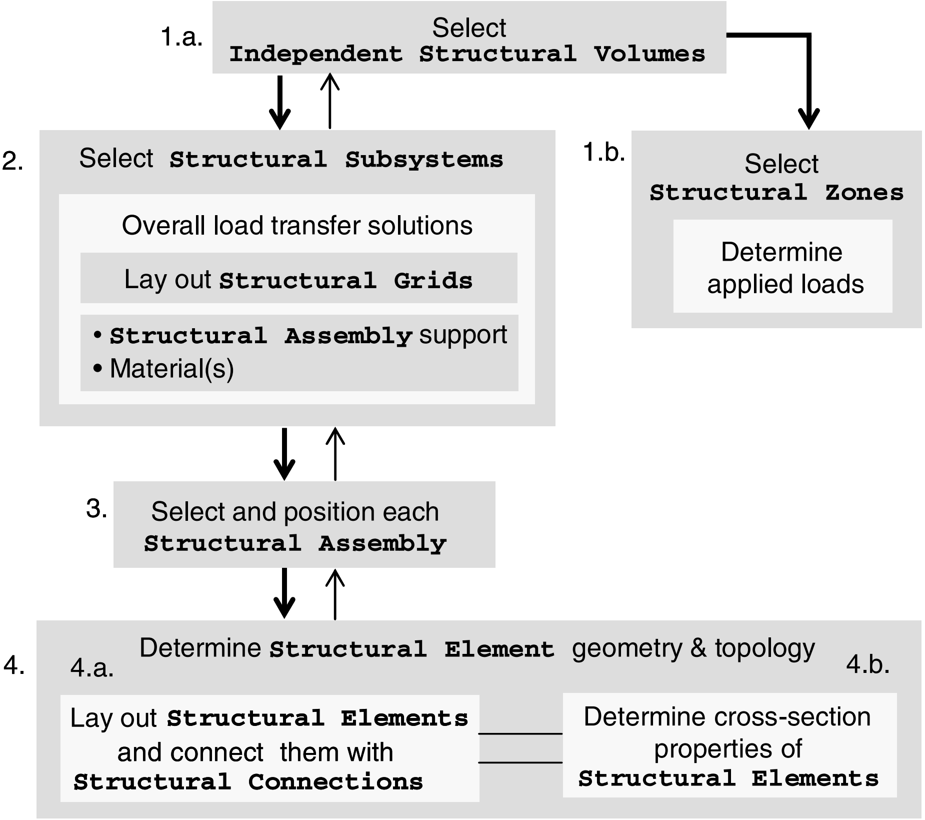

Fig. 1. Simplified conceptual structural design

defines overall load transfer solutions described in terms of supporting structural assemblies and corresponding material(s). Structural grids are also laid out during activity number 2 to assist in the validation of subsystem choices. These grids determine tentative vertical supports (at gridline intersections), structural bays, likely floor framing directions, and floor spans.

Interactivity is intended between a structural engineer, a simplified model of the building architecture and the structural system, Architecture-Structure Model (ASM) simplified for conceptual design, and a structural design knowledge manager (DKM). During the synthesis process, an architectural model is made available first to the engineer. Then, with the progressive use of knowledge from the DKM the structural system is integrated to the architecture and the result is an integrated architecture-structure model (ASM). Table 2 summarizes the types of interactions that take place at each step of the process between the engineer, the ASM and the DKM. In Table 2 a pre-processing and a post-processing activity in the process are included (unlike Figure 1). The pre-processing activity is an inspection of the architectural model, whereas the post-processing activity is the verification of the structural model.

As seen in Table 2 the main tasks performed by the engineer, the ASM and the DKM are the following:

(1) The engineer queries the ASM model, selects entities, specifies, positions and lays out assemblies and elements, and verifies structural solutions.
(2) The ASM model displays and emphasizes information accordingly, elaborates engineer's decisions, performs simple calculations on demand, and warns the engineer when supports are missing.
(3) The DKM suggests and ranks solutions, assigns loads, and elaborates and refines engineer's structural selections and layouts.

Each activity performed by the engineer advances a structural solution and provides the course of action to enable the ASM and the DKM to perform subsequent tasks accordingly. The knowledge-based exploration of structural alternatives takes place mostly at the abstraction levels of activities 2, 3, and 4 in Figure 1 and Table 2. At each subsequent level more information and knowledge is made available so that previously made decisions can be validated and more accurate ones can be made.

The implementation of the approach is based on an existing prototype for conceptual structural design called StAr (Structure-Architecture) that assists engineers in the inspection of a 3D architectural model (e.g. while searching for continuous load paths to the ground) and the configuration of structural solutions. Assistance is based on geometrical reasoning algorithms (GRA) [15] and an integrated architecture-structure representation model (ASM) [16]. The building architecture in the ASM representation model describes architectural entities such as stories, spaces and space aggregations, and space establishing elements such as walls, columns and slabs. The structural system is described in StAr as a hierarchy of entities to enable a top-down design approach. The geometric algorithms in StAr use the geometry and topology of the ASM model to construct new geometry and topology, and to verify the model. The algorithms are enhanced with embedded structural knowledge regarding layout and dimensional thresholds of applicability for structural assemblies made out of cast-in-place concrete. However, this knowledge is not sufficient for assisting engineers during conceptual design. StAr provides the kind of support described in the second column of Table 2, plus limited knowledge-based support (column 3) at levels 1.b and 4. Therefore, StAr is able to generate and verify a physical structure based on information obtained from precedent levels. However, no knowledge-based support is provided by StAr for exploration at levels 2, 3 and 4.

A structural design knowledge manager (DKM) is therefore developed that gets architectural and/or partial structural information from the ASM directly or via GRA to assist the engineer to conceive, elaborate and refine structural solutions interactively. Once the engineer accepts a solution suggested by the DKM, it automatically updates (i.e. elaborates or refines) the partial ASM. Architectural requirements in the form of model constraints (e.g. floor depths, column-free spaces, etc.) from the ASM model are also considered by the DKM for decision-making. The DKM encapsulates structural design knowledge by means of a set of technology nodes [17]. The type of knowledge incorporated in the nodes is heuristic and considers available materials, construction technologies, constructability, cost and

Table 2. Interactivity table between the engineer, the ASM and the DKM

Engineer	ASM	DKM
Architectural Model Inspection		
Query – Look for potential structural problems, continuous load paths to the ground and constraints. Select - Select elements that may become structural	Display the architectural model Emphasize continuous physical elements from this model Highlight architectural grids (i.e. main functional dimensions) Display global dimensional/layout constraints	N/A
1.a. Select `Independent Structural Volumes (ISV)`		
Query - Verify building shape, occupancies, lengths and proportions. Select - Select ISV by grouping spaces.	Emphasize spaces Compute overall building dimensions and aspect ratios	Suggest seismic/expansion joints if applicable
1.b. Select `Structural Zones`		
Query - Check types of spaces and associated constraints Select - Select structural zones by grouping spaces	Emphasize spaces Show space occupancies Display space layout/dimensional constraints	Assign loads to each zone based on its occupancy
2. Select `Structural Subsystems`		
Query - Inspect the model globally Select - Select structural subsystems and materials • Structural assembly support • Material(s) • Lay out structural grids	Display overall building characteristics Display global architectural layout/dimensional constraints Emphasize architectural elements selected to become structural	Suggest structural subsystems and materials Rank overall structural solutions
3. Select and position `Structural Assemblies`		
Select - Select each structural assembly Verify – Validate the initial description from level 2 Specify - Position each assembly Lay out - May determine preferred floor framing directions	Display structural grids Display applied loads Display local architectural layout/dimensional constraints Emphasize architectural elements selected to become structural	Suggest feasible structural assemblies Rank structural assemblies
4. Determine `Structural Element` geometry and topology		
Verify- Anticipate problematic supporting conditions locally Lay out - May position special structural elements and supports locally	Emphasize openings and irregularities in assemblies Elaborate - Make selected architectural elements structural Compute element loads based on tributary areas	Elaborate - Lay out and connect primary structural elements (within gridlines) Elaborate – Lay out and connect secondary structural elements Refine – Select preliminary cross-section shape and size of structural members
Structural system verification		
Verification - Verify and support still unsupported members Verification - Verify critical members	Warn about lack of supports and show unsupported elements	N/A

weight. A technology node represents the knowledge required to implement one design step (in the top-down hierarchy) utilizing a specific construction system or component. Nodes are organized into a hierarchy ranging from nodes dealing with abstract concepts (e.g. a structural subsystem) to those dealing with specific building entities (e.g. a reinforced concrete beam). The application of a technology node to a building entity from the ASM can be interpreted as making one decision about a design solution. Technology nodes support non-monotonic reasoning since they let the engineer retract any decision node and select another path in the technology tree.

A fundamental difference between this approach and the AI-based techniques discussed above is that here the architectural model is created by an architect and not by an architecturally constrained AI system, and alternative structural subsystems and layouts are proposed by the engineer and not by the computer. The computer only evaluates alternatives and suggests solutions on demand. Following this approach, significant advantages accrue over commercial applications for structural model generation: (1) it facilitates design exploration by proposing feasible design alternatives and enabling non-monotonic reasoning, (2) it constitutes a more efficient method for conceptual structural design because it simplifies the design problem by decomposition/refinement, (3) it enables more integrated design solutions because it uses structural design knowledge to evolve an architecturally constrained building information model, and (4) it facilitates decision-making and early architect-engineer negotiations by providing quantitative evaluation results. This research work is in progress. A more detailed description is given elsewhere [13].

5 Conclusions

Practitioners in the AEC industry have benefited from computing and IT tools for a long time, yet the industry is still profoundly fragmented in North America, which translates into poor productivity and a lack of innovation compared to other industrial sectors. Recent surveys reveal a contradiction in the adoption of new technologies: on the one hand, they appear to be used in many tasks performed by the majority of stakeholders in the industry, yet on the other hand, they fall short of delivering as promised, thus leaving practitioners to contend with new complexities, constraints and costs that make them stick with traditional approaches, with the attending poor performance. The fact that critical human factors are not given due consideration in the development of new computing and IT tools can explain in part why such technologies are often not adopted by the practice as readily as expected. In this context, the development of integrated approaches would appear highly effective in counteracting the currently fragmented approaches to multidisciplinary building design. An on-going research project is presented briefly to illustrate innovative ways of advancing integration in the conceptual design of building structures.

References

1. Bédard, C. and Rivard, H.: Two Decades of Research Developments in Building Design. Proc. of CIB W78 20th Int'l Conf. on IT for Construction, CIB Report: Publication 284, Waiheke Island, New Zealand, April 23-25, (2003) 23-30
2. Rivard, H.: A Survey on the Impact of Information Technology on the Canadian Architecture, Engineering and Construction Industry. Electronic J. of Information Technology in Construction, 5(http://itcon.org/2000/3/). (2000) 37-56
3. Rivard, H., Froese, T., Waugh, L. M., El-Diraby, T., Mora, R., Torres, H., Gill, S. M., & O'Reilly, T.: Case Studies on the Use of Information Technology in the Canadian Construction Industry. Electronic J. of Information Technology in Construction, 9(http://itcon.org/2004/2/). (2004) 19-34

4. Chiocchio, F., Lacasse, C. Rivard, H., Forgues, D. and Bédard, C.: Information Technology and Collaboration in the Canadian Construction Industry. Proc. of Int’l Conf. on Computing and Decision Making in Civil and Building Engineering, ICCCBE-XI, Montréal, Canada, June 14-16, (2006) 11 p.
5. Howard, R.: IT Directions – 20 Years’ Experience and Future Activities for CIB W78. Proc. of CIB W78 20th Int’l Conf. on IT for Construction, CIB Report: Publication 284, Waiheke Island, New Zealand, April 23-25, (2003) 23-30
6. Fenves, S.J. and Rivard, H.: Generative Systems in Structural Engineering Design. Proc. of Generative CAD Systems Symposium, Carnegie-Mellon University, Pittsburgh, USA (2004) 17 p.
7. Bédard, C.: Changes and the Unchangeable : Computers in Construction. Proc. of 4th Joint Int’l Symposium on IT in Civil Engineering, ASCE, Nashville, USA (2003) 7 p.
8. IAI (International Alliance for Interoperability) www.iai-international.org (2006)
9. NIST (National Institute of Standards and Technology): Cost Analysis of Inadequate Interoperability in the US Capital Facilities Industry. NIST GCR 04-867 (2004)
10. Bédard, C. and Gowri, K.: KBS Contributions and Tools in CABD. Int’l J. of Applied Engineering Education, 6(2), (1990) 155-163
11. Khemlani L.: AECbytes product review: Autodesk Revit Structure, Internet URL: http://www.aecbytes.com/review/RevitStructure.htm (2005)
12. Bailey S. and Smith I.: Case-based preliminary building design, ASCE J. of Computing in Civil Engineering, 8(4), (1994) 454-467
13. Mora, R., Rivard, H., Parent, S. and Bédard, C.: Interactive Knowledge-Based Assistance for Conceptual Design of Building Structures. Proc. of the Conf. on Advances in Engineering, Structures, Mechanics and Construction. University of Waterloo, Canada (2006) 12 p.
14. Rivard H. and Fenves S.J.: A representation for conceptual design of buildings, ASCE J. of Computing in Civil Engineering, 14(3), (2000) 151-159
15. Mora R., Bédard C. and Rivard H.: Geometric modeling and reasoning for the conceptual design of building structures. Submitted for publication to the J. of Advanced Engineering Informatics, Elsevier (2006)
16. Mora R., Rivard H. and Bédard C.: A computer representation to support conceptual structural design within a building architectural context. ASCE J. of Computing in Civil Engineering, 20(2), (2006) 76-87
17. Fenves S.J., Rivard H. and Gomez N.: SEED-Config: a tool for conceptual structural design in a collaborative building design environment. AI in Engineering, 14(1), Elsevier, (2000) 233-247