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INTEGRATION OF BIM AND GENERATIVE DESIGN TO EXPLOIT AEC CONCEPTUAL DESIGN INNOVATION

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SUMMARY: *New technological advancements in Architecture-Engineering-Construction (AEC) design has brought the 'level of automation' as a pivotal factor in the success of projects. One of the key debates in 'effective automation' is its congruence throughout the AEC projects. This is currently hampered due to the failures in computational support at the early conceptual design stages. Yet, these failures are significant, and have direct impact upon the success of the AEC design process. Extant literature has identified a significant knowledge gap concerning the key impact links and support mechanisms needed to overtly exploit computational design methods, especially Building Information Modelling (BIM), throughout the conceptual design stage. This study posited that integration of generative design algorithms to the existing BIM platforms could bridge this gap by generating design solutions and transforming them into next stages of detailed design. This paper reports on the conducted survey to investigate perceptions of 153 professionals and students and articulate their approach to different angles of such a technology. Most of the respondents highlighted several deficiencies in the existing tools, whilst they asserted that such a purposeful BIM interface can offer comprehensive support for automation of the entire of AEC design and implementation phases, and particularly enhance the decision making process at the early design phases. Building upon two main constructs of the conducted survey, namely information modelling and form generation, this study further developed conceptual framework for 'virtual generative design workspace' using BIM as the central conduit. The details of this framework are presented in this paper. The developed framework will be used to develop a 'proof of concept' prototype, to actively engage generative design methods into a single dynamic BIM environment. This study contributes by forming a stepping stone for digital integrating of all stages of AEC projects and implementing BIM Level 3 (Cloud), as targeted by many countries.*

KEYWORDS: *Automation, AEC, BIM, Generative design, Parametric design, Computational design, Computer-based environment.*

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1. INTRODUCTION

In the AEC practice, designers explore different design possibilities by producing multiple design solutions which independently demands parallel redundant effort throughout the design process (Succar 2011). One of the key debates when it comes to modern methods of building design and construction is the level of automation throughout the process (Frohm et al. 2008; Skibniewski et al. 2013). This could include justifying automation in construction with a high product variety and significant variations in demand (which entails flexible and reconfigurable manufacturing systems (Colombo and Harrison 2008), effective/cohesive supply chains, and integration of instinctive design modelling, simulation and decision support systems (Fruchter 1998).

This integration is not so apparent in current AEC projects, where designers start employing advanced visualisation and modelling technologies only at the very late design stages. Consequently the design knowledge is mainly not captured (and lost) during early conceptual phase, where the most vital decisions are made. Pour Rahimian and Ibrahim (2011) linked this problem to the non-intuitive interface of the conventional Computer Aided Design (CAD) tools which make them not suitable for supporting the type of reasoning and cognition which appear during conceptual design phases. In order to bridge this gap, Lee et al. (2013) advocated the potential of using parametric design interfaces as a new paradigm in the field of CAD (and BIM), as the mechanisms which are capable of producing design alternatives controlled by certain rules or limits, regardless of modelling and visualisation skills of designers. This approach has been praised for improving designers' design creativity by allowing designers to use synectics as an idea seeding technique (Blosiu, 1999), while supporting the design process through the unproblematic generation of design alternatives (Kim and Kang, 2003) through altering various design parameters and observing (and reflecting on) the results in real-time (Goulding and Pour Rahimian 2012).

Amongst the emerging design automation systems, generative systems have been assisting designers to rapidly explore design solutions and can enhance designer by saving time and effort and assess more possible alternatives to the design requirements (Narahara et al. 2006). Whilst generative tools assist AEC designers in their design projects, it fails to meet the very basic principles of information modelling and data management requirements. In order to address this problem, Abrishami et al. (2013) proposed the development of *'Generative BIM workspace'* which enables design creativity, fluidity, and flexibility by the adoption of generative design approach; at the same it makes minimal changes to the common design process. They argued that using such an integrated platform, relevant information to the design requirements can form the system input, whereas the design algorithms can generate the design output. They also argued that this platform integration can assist designers to solve complex multi-criteria design problems.

This paper presents the results of a conducted survey to explore different User Requirements Specifications (URSs) and various angles of integration of generative design algorithms to the existing BIM platforms. The main objective of this survey was to develop conceptual framework of the Generative BIM platform for maximising the efficiency of design teams and outline a new method for BIM applications to support throughout design process; i.e. from very early conceptual design stages to final detailed design phases. Therefore, the survey was designed based on two main constructs, namely information modelling and form generation.

2. LITERATURE REVIEW

The focus of contemporary AEC design projects is increasingly moving from an architecture with aesthetical emphasis towards performance (structure, environment, construction, socioeconomically and cultural, etc.) based architecture (Roudavski 2009). This shift in design attitude is inviting architecture to adopt new technologies that can support this transition. The AEC designers started adopting technology from industrial design, mechanical engineering and product developments, where performance tends to play a crucial role, as well as adopting new computational design methods such as generative and parametric approach, isomorphic surfaces, kinematics and dynamics, topological space are also being engaged.

Given these changes and new inertia, the research explores the potential of a BIM design environment integrated with new computational design methods in order to maximise their opportunities. The proposed framework exploits generative design for creation of alternatives at early design stages, and existing parametric algorithm in BIM tools for modification of the chosen alternative(s) and change management during the late design stages up to the construction level. The following sections present a more detailed description of each individual feature of the proposed environment.

1 Building Information Modelling

As construction projects increase in complexity, alternative modern methods of construction and design increase in popularity (Cooke and Williams 2009). Suermann (2009) pointed out that BIM has been used by designers, construction managers and contractors who have the ability to accomplish tasks more efficiently than ever before and pave the way for future construction professionals. Furthermore, clients increasingly require BIM services from the designers and contractors. There are many definitions of what BIM is and in many ways it depends on the point of view is looked at or what is sought to gain from the approach. There are two most common definitions. In the UK, the Construction Project Information Committee (CPIC) has defined BIM as: *"...digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition"* RIBA (2012: 3). In the USA, the National BIM Standard has defined BIM as *"a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward"* (NBIMS-US 2007: 21).

The Building Information Model is primarily a 3D digital representation of a facility and its core characteristics. It consists of intelligent structural components which includes data attributes and parametric rules for each object. For instance, a library of certain materials, shape and dimensions is parametrically related and hosted by a wall. Furthermore, BIM provides constant and coordinated views and representations of the digital model including reliable and updated data and for each view. BIM is increasingly becoming a better known established collaboration process in the design and construction process of buildings.

2 Parametric Design

This approach is taken in late design stages in order to find the best solution to the design problem amongst different design alternatives. A basic design concept is established in advance. Thereafter, components parameterised by the designer for further improvement. Some examples of parametric evolutionary systems are Rasheed (1998), Dasgupta et al. (1997), Monks et al. (2000), Obayashi et al. (2000), Caldas (2004), and Sasaki et al. (2001). Application of parametric design has been successfully adopted in a number of BIM applications as a change management engine (Eastman 2004). However parametric systems have evolved into effective design tools, but still they are not considered as comprehensive AEC design applications.

3 Generative Design

Generative design refers to any design practice where the designer uses a system, such as a computer programme, to produce the solution to the design problem with some level of autonomy. Although current generative systems could provide assistance to designers by the process of creation of models and solution alternatives, they fail to meet necessary requirement for AEC designers. Therefore, this research proposes the application of evolutionary algorithm for the generation of design alternatives within the BIM environment. It is advocated that this approach could enhance the system's capabilities by allowing the generation of complex forms with various details and layout that would not be possible without using such a system. Several researchers have highlighted the benefits of using evolutionary design (Frazer 2002; Bentley 1999; Janssen 2006; Mirtschin 2011; Narahara et al. 2006).

The purpose of this research is not to epitomise existing systems and approaches per se, rather, the research endeavour is to optimise the design process by integrating different existing approaches. The evolutionary design method uses evolutionary software systems (such as genetic algorithm, cellular automata, L-systems, swarm intelligence and shape grammars) in order to enhance designers' ability during the design process. Evolutionary design is broadly recognised by the parametric evolutionary design and generative evolutionary design (Janssen 2006).

3. RESEARCH METHODOLOGY

The aim of this study was to empirically develop detailed URSs for the Generative BIM framework. The study employed survey methodology (using Bristol Online Survey (BOS) tool) as the method of data collection to evaluate the perceptions of professionals and researchers towards a solution for conceptual design automation. In accordance to the two main constructs of the study (i.e. information modelling and form generation), the main focus of the questionnaire was on the issues such as automation at conceptual design stages, modelling tools, BIM, generative design, and integration of BIM and generative design to evaluate BIM's potential for exploiting generative design through the conceptual design. These questions were developed based on the results of a detailed qualitative study by Abrishami et al. (2013). A pilot test was also conducted amongst selected participants of the target groups (professionals in research and practice, and students) in the field of AEC design. Thereafter, the questionnaire was iteratively amended based on the feedback provided by the test, for instance one of these amendments was preparing three separate questionnaires with comparable questions for the three different target groups instead of putting forward just one single questionnaire.

In terms of questionnaire design, this study relied on both academia and practice. This is because academia plays an important role in the development and testing of such systems, while the development of specific components stem from the needs of practice. Evaluating and testing computational design tools in an academic setting, fosters creativity and generates many unforeseen applications. The aim of the advanced design technology theme is to encourage industry and academia in using, adapting and creating new tools for design. The data was collected via a pre-piloted web-based survey. Based on the pilot studies, the questionnaire took an average of 10 minutes. The core survey questions consisted of several 4-points Likert scales, multiple choices, and polar questions. Additional or extraneous comments were accepted as non-required materials. The questionnaire was comprised of three sections: First section took into account the general information regarding the participants' professional role and experience; section 2 consisted of 6 questions about various design paradigms including digital design, computational modelling, BIM, and generative design; section 3 focused on the proposed conceptual framework and participants' opinion regarding different features of that framework was aimed for.

The sample size for the survey was calculated at 95 per cent Confidence Level, with the assumed Confidence Interval of 5. The study also applied Stratified sampling method (Kumar 2005) for purposefully selecting respondents who are currently using at least one BIM software applications in their works or have published research articles on BIM. In accordance to this criterion, the size of population in the context of the UK was not definitely greater than 1000. As such, the calculated sample size based on the mentioned criteria was 278. As a result of sending 278 invitations to the purposefully selected target respondents, the study received total of 153 valid responses from: 30 *Researchers*, 38 *Professionals in Practice*, and 85 *Students*.

For analysis of data, statistical data was coded and stored as an SPSS data file. In this regard, SPSS version 20 was used to facilitate the descriptive and inferential statistical analysis. A number of statistical analysis methods were employed to examine the relationship between dependent and independent variables of this research. These methods included basic descriptive statistics as well as examination of scale reliability, ANOVA (for assessing significant differences between and within groups) and Chi square (for assessing significant relationships). The result of SPSS analysis has been presented in both quantitative (e.g. frequency, percentages, mean values) with the use of graphs, tables and qualitative methods (e.g. statements and description).

4. RESULTS AND ANALYSIS

1 Computational support/BIM at conceptual design

With respect to *using computers at the conceptual design stage*, the distributions of categorical variables differed from one another, therefore, the percentage of participants from different target groups, attempting to employ computers at the conceptual design stage underwent statistical significance (χ^2 (4) = 11.305, p = .023). Researchers and students reported difficulties in using computers at the early design stage (researchers: χ^2 (2) = 11.4, p = .003, students: χ^2 (1) = 14.412, p = .000), whereas, there is no statistical significance for professionals in practice and 55.3% of them have stated that they have difficulties in using computers at the conceptual design stage (χ^2 (1) = .421, p = .516). This can be due to the nature of the projects they are involved in (limitations). TABLE 1 reveals a summary of the results.

With regards to *using computers to design complicated shapes,* all the three groups of participants stated that they struggled to use computers for creating complicated forms (*practice:* χ^2 (2) = 11.421, *p* = .003, *students:* χ^2 (2) = 39.412, *p* = .000, *researchers:* χ^2 (2) = 16.8, *p* = .003) and the results obtained are statistically significant in all groups (χ^2 (4) = 9.545, *p* = .049). A summary of the results are presented in TABLE 1.

Regarding the *integration of Generative Design and BIM as a solution*, there were different percentage of the participants voting in favour of, against and not sure of the idea that integration could overcome the difficulties in using computers and designing complicated shapes at conceptual design stage (χ^2 (4) = 35.719, *p* = .008). The percentage of practitioners and students voted in favour of the integration were statistically significant (Practice: χ^2 (2) = 37, *p* = .000, students: χ^2 (1) = 7.353, *p* = .007), and 50% of professionals in research stated *"yes"*, 10% stated *"no"*, and 40% stated *"not sure"* and these percentages were statistically significant (χ^2 (2) = 7.8, *p* = .02). TABLE 1 reveals a summary of the results.

TABLE 1: Computational support at the conceptual design stage.

		Struggle during early design stages			Struggle in designing complicated shapes			Integration of BIM and Generative Design overcome the above challenges		
		Not Sure	NO	Yes	Not Sure	NO	Yes	Not Sure	NO	Yes
Groups	Practice	0.0%	44.7%	55.3%	7.9%	50.0%	42.1%	18.4%	2.6%	78.9%
	Students	0.0%	29.4%	70.6%	11.8%	23.5%	64.7%	35.3%	0.0%	64.7%
	Research	6.7%	36.7%	56.7%	6.7%	26.7%	66.7%	40.0%	10%	50.0%
Total		**1.3%**	**34.6%**	**64.1%**	**9.8%**	**30.7%**	**59.5%**	**32.0%**	**2.6%**	**65.4%**

2 Integration of BIM and Generative Design

The survey results reveal that the proposed framework can improve designers' capabilities at conceptual stage. All the three categories of participants highlighted the importance of BIM for AEC projects and regarded the integration of BIM and Generative Design as a solution for BIM deficiencies at the conceptual design stage.

An ANOVA (Analysis of Variance) test was performed to assess whether the mean differences of independent groups were statistically significant or not. The ANOVA test is based on two underlying assumptions. First, either the data must have normal distribution or the sample size must be large. In our research, the sample size of practitioners, students and researchers were 38, 85, and 30 respectively. Therefore, CLT (Central Limit Theorem) was adopted in order to use ANOVA test for Likert Scale data. The second assumption was that the groups must come from populations with equal variances. To question this assumption, Levene's homogeneity-of-variance test was performed. In the ANOVA test whenever this assumption was not satisfied, Welch's t test was applied instead of F statistic. To follow up the statistical significance Tukey test (in case the assumption about the equality of variance was not violated) or Dunnett T3 (when the assumption of the equality of variance was violated) was used. In the following paragraphs the results of each part of the question is represented based on the aforementioned method (Table 2).

With respect to the *importance of BIM in the AEC projects*, the results reveal that viewpoints towards attaching importance to the role of BIM in AEC projects fluctuate between "*Agree & Strongly Agree*" (practice *M* = 4.68, SD = .525; students *M* = 4.41, SD = .603; and researchers *M* = 3.83, SD = 1.206), and there was a statistical significance (Welch (2, 60.254) = 7.642, *p* = .001). The assumption about the equality of variances were violated (Leven (2, 150) = 26.556, *p* = .000) and as it is illustrated in the Fig. 1a, Dunnett T3 test shows that the practitioners, students and researchers' level of agreement on this issue is on a descending order.

Regarding the *importance of Generative Design in the computational design,* the results similar to that of the previous section were obtained concerning the role of generative design in AEC projects, labelling strong disagreement to strong agreement with numbers from 1 to 5. All the categories considered generative design to play a vital role in AEC design projects (practice M = 4.13, SD = 1.044; students M = 4.12, SD = .680, and researchers M = 3.67, SD = 1.028), and there was no statistical significance (Welch (2, 55.857) = 2.551, p = .087). Here the assumption about the equality of variances were violated (Leven (2, 150) = 4.584, p = .012).

TABLE 2: Integration of BIM and Generative Design.

	BIM is the future of building design and project information			Generative Design become a vital computational design paradigm			Adoption of Generative Design by architects			Integration of BIM and Generative Design support conceptual design			CAD or BIM		
	N	M	SD	N	M	SD	N	M	SD	N	M	SD	N	M	SD
Practice	38	4.68	.525	38	4.13	1.044	38	4.42	.948	38	4.47	.797	38	4.39	1.028
Students	85	4.41	.603	85	4.12	.680	85	4.00	.772	85	4.29	.574	85	3.94	1.062
Research	30	3.83	1.206	30	3.67	1.028	30	3.97	.850	30	3.93	1.048	30	4.00	.910
Total	**153**	**4.37**	**.793**	**153**	**4.03**	**.869**	**153**	**4.10**	**.849**	**153**	**4.27**	**.761**	**153**	**4.07**	**1.037**

With regards to the *adoption of Generative Design for design creativity*, the practitioners' level of agreement fluctuated between "*Agree & Strongly Agree"* while the researchers and students rated the question as "*Agree"* (practice M = 4.42, SD = .948; students M = 4.00, SD = .772; and researchers M = 3.97, SD = .850) and it was statistically significant (F (2, 152) = 3.813, p = .024). Here the assumption about the equality of variances was violated (Leven (2, 150) = .312, p = .732) and Tukey test shows that the students and researchers have the same level of agreement which is less than that of practitioners on this issue (Fig. 1b).

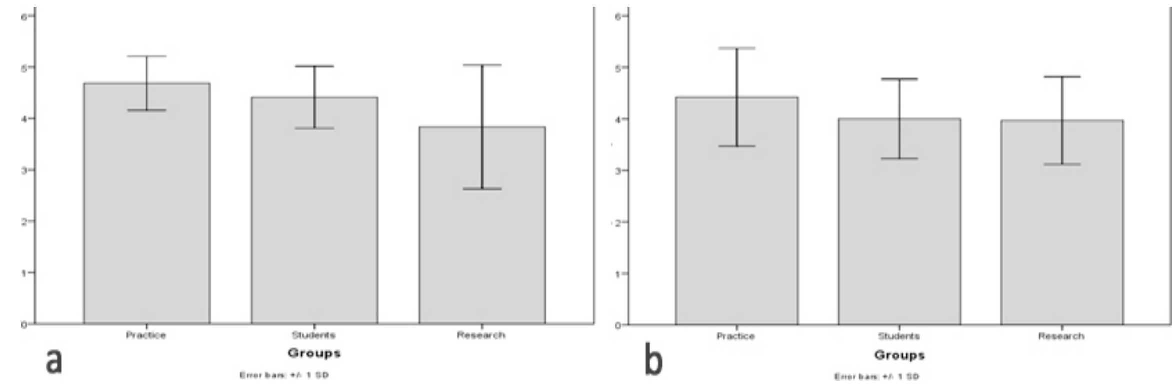

FIG 1: a. Dunnett T3 result for importance attributed to BIM.

b. Tukey test result for Generative Design adoption.

With respect to the *integration of BIM and Generative Design*, the professionals in practice and students rated the question as "*Agree & Strongly Agree*" but the researchers rated it as "*Agree*" (practice M = 4.47, SD = .797; students M = 4.29, SD = .574; and researchers M = 3.93, SD = 1.048). Here there was no statistical significance (Welch (2, 55.013) = 2.7.0, p = .076) and the assumption of equality of variances was violated (Leven (2, 150) = 7.143, p = .001).

With regards to the applicability of *CAD or BIM* for the proposed framework, there was a consensus among all the three categories of participants on integrating BIM with Generative Design (practice $M = 4.39$, SD = 1.028; students $M = 3.94$, SD = 1.062; and researchers $M = 4.00$, SD = .910). Here there was no statistical significance (F (2, 152) = 2.644, $p = .074$) and the assumption about equality of variances was violated (Leven (2, 150) = .403, $p = .669$).

3 Expanding the designers' capabilities and enhancement of BIM by computational idea generation

As it can be seen in Table 3, all the three target groups indicated that Generative Design had exerted a significant influence on developing the designers' capabilities. The proportion of participants chosen *"yes"* or *"no"* or *"not sure"* as their answers was relatively the same in all groups. To follow up the statistical significance, Chi-squared test was used, which showed no statistical significance here (χ^2 (4) = 3.835, $p = .429$). The percentage of participants in agreement on the positive contribution of Generative Design towards their design abilities is statistically significant (practice: χ^2 (1) = 20.632, $p = .000$, students: χ^2 (2) = 92.353, $p = .000$, research: χ^2 (2) = 24.065, $p = .000$).

As Table 3 also illustrates, all the three target groups pointed towards the considerable influence of the Generative Design on the enhancement of BIM. In all groups there was similar proportion of participants chosen *"yes"* or *"no"* or *"not sure"* as their answers. In order to investigate the statistical significance Chi-squared test was done that proved the existence of statistical significance in this case (χ^2 (4) = 10.084, $p = .039$). The percentage of participants regarding Generative Design as a help leading to improvement of their design abilities is statistically significant (practice: χ^2 (1) = 17.789, $p = .000$, students: χ^2 (2) = 92.353, $p = .000$, research: χ^2 (2) = 14, $p = .001$).

TABLE 3: Increasing designers' capabilities by using computational idea generation & Potential role of computational idea generation in BIM tools.

		Computational idea generation enhance designers' capabilities?			Computational idea generation can enhance BIM capabilities?		
		Not Sure	NO	Yes	Not Sure	NO	Yes
Groups	Practice	13.2%	0.0%	86.8%	15.8%	0.0%	84.2%
	Students	11.8%	5.9%	82.4%	11.8%	5.9%	82.4%
	Research	20.0%	6.7%	73.3%	33.3%	6.7%	60.0%
Total		**13.7%**	**4.6%**	**81.7%**	**17.0%**	**4.6%**	**78.4%**

5. CONCEPTUAL FRAMEWORK OF GENERATIVE BIM WORKSPACE

The results highlighted that recent developments in computational design have substantially changed conventional design process, therefore, designers' way of working. The results also indicated that many of the available systems are capable of handling complex design processes that vary in overall organisation and configuration by the designer. However, it has been revealed that none of these systems are fully capable of purposefully manipulating conceptual design. In order to overcome this barrier, this research proposes a system which combines new concepts in an existing BIM environment. The proposed framework uses generative design for conceptual design and form generation (population of alternatives); coupled with advanced BIM features for illustration, collaboration, and parametric change management.

Integration of generative tools with information modelling combined with advanced 3D knowledge-rich systems is creating new potential for designing and coordinating amongst various stakeholders in AEC (Kocaturk and

Medjdoub 2011). The use of generative design can be defined as exploitation of parameters created in the early design stages. Since the generated solutions to the design problem (population of design alternatives) are the results of an algorithm (consisting design constraints, routines, and data files) by changing the inputs of the algorithm, the final design would be altered accordingly, like creating a basic model based on 'Routines', and generating different design alternatives by adjusting very basic design parameters.

Moreover, material, fabrication constraints, and assembly logics are parameterised in response to the environment. Generative process of designing is capable of linking the geometric behaviour patterns and performance properties of the system. The design environment is constantly connected to the external environment; therefore, external behavioural tendencies alter the ontogenies through parametrisation (Hensel and Menges 2008). Such an approach was used to shape, inform, and provide granular data to help identify the delimiters. The described method used to help shape schema for the research model. Fig. 2 presents an outline of the proposed Generative BIM environment conceptual framework.

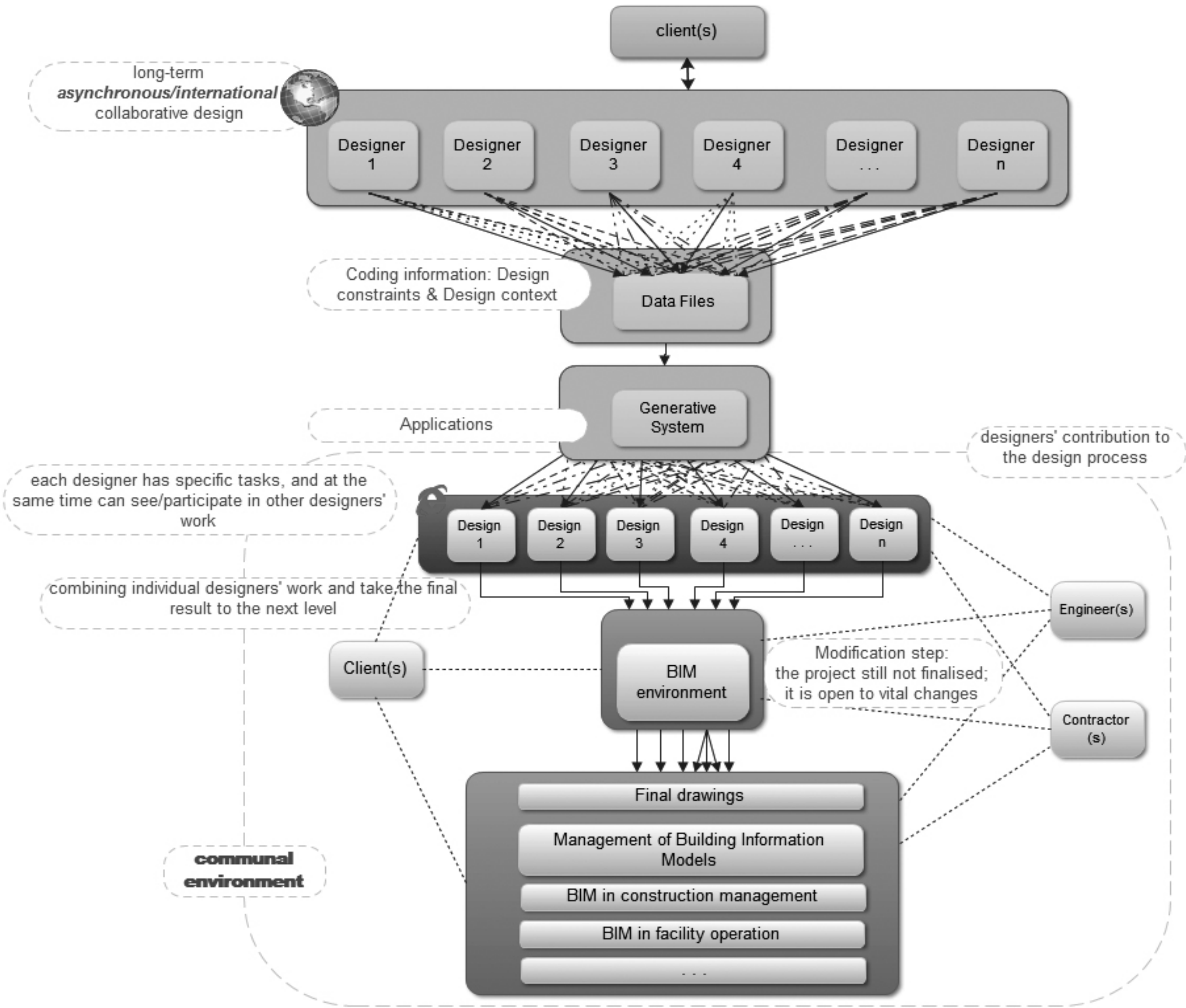

FIG 2: Conceptual Framework for Generative BIM Environment.

6. CONCLUSION

Construction projects are increasingly becoming more complex, often engaging new business processes and technological solutions in line with projects' requirements. Moreover, it is advocated that the AEC sector in particular is likely to require a myriad of increasingly advanced technologies in order to meet the new architectural paradigm requirements, and coping with recent complicated AEC projects.

The research provides insights into professionals in research and practice, and students difficulties during conceptual design stage, especially with using computers. Moreover, the research gained valuable feedback on the proposed conceptual framework for the development phase of the research. The research has also identified specific structured limitations of existing BIM and generative tools, and proposes a Generative BIM framework which is capable of: providing techniques for exploring and generating design solutions, creating of models with relevant links to all required information and details for the development process; along with creating a generative process capable of controlling the variability of design outcomes, generation of designs with the required level of complexity, and generate alternatives that differ significantly in terms of overall organisation and configuration. Moreover, it is posited that in order to address the entire requirements for BIM Level 3 (Cloud), a fully integrated system that supports all members of professional and construction team including AEC designers is a vital necessity. Development of this research has presented and assessed (through a survey) a conceptual framework for exploitation of new concepts in computational design and architecture. The theoretical basis developed through this research could be used for development of a working prototype. In essence, further studies are needed to develop and validate this framework, using domain experts and focus-groups (development iteration); to capture the precise rubrics and parameters needed to shape this model as a part of the development process.

REFERENCES

Bentley, P (1999) "An introduction to evolutionary design by computers". California: Morgan Kaufmann Publishers, 1-73.

Blosiu, J. O. (1999). Use of synectics as an idea seeding technique to enhance design creativity. Paper presented at the Systems, Man, and Cybernetics, 1999. IEEE SMC '99 Conference Proceedings. 1999 IEEE International Conference on, 1999.

Caldas, L G, and Norford, L K (2004) Shape generation using pareto genetic algorithms: Integrating conflicting design objectives in low energy architecture. "International Journal of Architectural Computing", 1(4), 503-515.

Colombo, A W and Harrison, R (2008) Modular and collaborative automation: achieving manufacturing flexibility and configurability. "*International Journal of Manufacturing Technology and Management*", 14, 249-265.

Cooke, B. and Williams, P., 2009. *Construction Planning, Programming and Control*, 3rd ed., Wiley Blackwell, UK.

Dasgupta, D and Michalewicz, Z (1997) "Evolutionary algorithms in engineering applications Springer-Verlag". Springer.

Eastman, C, Sacks, R and Lee, G (2004) Functional modeling in parametric CAD systems, GCAD2004.

Finkelsteiin, F., 1994. Software Process Modelling and Technology. Jeff Kramer and Bashar Nuseibeh (Eds.). John Wiley & Sons, Inc., New York, NY, USA.

Frazer, J H and Connor, J (1999) A conceptual seeding technique for architectural design. "International conference on the application of computers in architectural design and urban planning (PArC79)", 1999, AMK berlin, 425–434.

Frazer, J H (2002) Creative design and the generative evolutionary paradigm. In: Bentley and Corne (2002), 253-274.

Frohm, J., Stahre, J., and Winroth, M. (2008). Levels of automation in manufacturing. Ergonomia - an International journal of ergonomics and human factors, 30(3).

Fruchter, R. (1998). Internet-based web-mediated collaborative design and learning environment. In I. Smith (Ed.), Artificial Intelligence in Structural Engineering (Vol. 1454, pp. 133–145). Berlin: Springer.

Goulding, J. S., & Rahimian, F. P. (2012). Industry Preparedness: Advanced Learning Paradigms for

Exploitation. In A. Akintoye, J. S. Goulding & G. Zawdie (Eds.), Construction Innovation and Process Improvement (pp. 409-433). Oxford, UK: Wiley-Blackwell.

Hensel, M and Menges, A (2008) Versatility and Vicissitude - Performance in Morpho-Ecological Design. “AD Architectural Design”, Vol. 78, 2.

Kim, Y. S., and Kang, B. G. (2003). Personal Characteristics and Design-Related Performances in a Creative Engineering Design Course. Paper presented at the The 6th Asian Design Conference, Tsukuba, Japan.

Kocaturk, T and Medjdoub, B (2011) “Distributed Intelligence In Design”. Hardcover edition, Wiley-Blackwell.

Kumar, Ranjiti (2005). Research methodology, a step-by-step guide for beginners. London: SAGE Publications.

Janssen, P (2006) A generative evolutionary design method. “Digital Creativity”, 17(1), 49–63.

Lee, J., Gu, N., Ostwald, M., and Jupp, J. (2013). Understanding Cognitive Activities in Parametric Design. In J. Zhang and C. Sun (Eds.), Global Design and Local Materialization (Vol. 369, pp. 38-49): Springer Berlin Heidelberg.

Mirtschin, J (2011) Engaging Generative BIM Workflows, “IABSE-IASS conference”, London.

Monks, M, Oh, B M and Dorsey, J (2000) Audioptimization: Goal-based acoustic design, “IEEE computer graphics and applications”. 20(3), 76–91.

National BIM Standard-US (NBIMS-US) (2007) United States: The National Building Information Model Standard, Version 1 - Part 1.{ http://www.wbdg.org/pdfs/NBIMSv1_p1.pdf} [access on 04/04/ 2013].

Narahara, T (2006) Multiple-constraint Genetic Algorithm in Housing Design, Synthetic Landscapes, “Proceedings of the 25th Annual Conference of the Association for Computer-Aided Design in Architecture”, 418-425.

Obayashi, S, Sasaki, D, Takeguchi, Y and Hirose, N (2000) Multiobjective evolutionary computation for supersonic wing-shape optimization, “IEEE transactions on evolutionary computation”. 4(2), 182-187.

Rahimian, F. P., and Ibrahim, R. (2011). Impacts of VR 3D sketching on novice designers' spatial cognition in collaborative conceptual architectural design. *Design Studies, 32*(3), 255-291.

Rasheed, K M (1998) “GADO: A genetic algorithm for continuous design optimization”. Unpublished PhD Thesis, Department of Computer Science, Rutgers University, New Brunswick, NJ.

RIBA (2012) BIM Overlay to the RIBA Outline Plan of Work. http://www.bdonline.co.uk/Journals/2012/05/15/d/x/f/BIM_Overlay_RIBA_Plan_of_Work_Embargoed.pdf [accessed on 04/04/2013].

Roudavski, S (2009) Towards Morphogenesis in Architecture. “International journal of architectural computing”, Vol 07, Issue 03, 345-374.

Sasaki, D, Morikawa, M, Obayashi, S and Nakahashi, K (2001) Aerodynamic shape optimization of supersonic wings by adaptive range multiobjective genetic algorithms, “proceedings of evolutionary multi-criterion optimization: First international conference EMO 2001”, 1993, Zurich, Switzerland, 639–652.

Skibniewski, M. J., and Zavadskas, E. K. (2013). Technology development in construction: A continuum from distant past into the future. Journal of Civil Engineering and Management, 19(1), 136–147. doi:10.3846/13923730.2012.756060.

Succar, B. (2011). Organizational BIM; How to assess and improve your organization's BIM performance. Paper presented at the Revit Technology Conference Australasia, V1.1, session 3 part B.

Suermann, P (2009) Evaluating industry perceptions of building information modelling (BIM) impact on construction. “International Journal of IT in Construction”, Vol. 14, 574–594.

Sun, J, Frazer, J H, Mingxi, T (2007) Shape optimisation using evolutionary techniques in product design, "Computers and Industrial Engineering", Vol. 53, Issue 2, 200-205.