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Computation as ‘Intervention’: A Systematic Review of ‘Outcome’

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‘Meta-analysis’, a quantitative technique widely used for the systematic review of randomised control trials in medicine, is deployed as a method to identify studies which investigate computer aided design software as an ‘intervention’ with causality, complexity and creativity as design ‘outcomes’. The paper hypothesises ‘a cause-and-effect’ relationship between ‘tools’ and design ‘outcome’ and infers that, contrary to held beliefs, tools are not passive; there may-be a design phenomenon of tool-linked ‘causality’. To this end Heidegger’s text on the act of ‘revealing’ surrounding the use of technology was deductively used. The study then links the issue of tools to design creativity through a two-stage process. First, creativity domains were culled from seminal works. Second, the impact of computer tools on creative problem-solving and ideation was examined empirically through an original design algorithm developed by the author. In brief, computer-augmented creativity in design is feasible for form finding, complexity optimisation and ideation variety.

Keywords: causality, systematic review, creativity, tools, meta-analysis

1 Introduction: The research problem

The impact of using representation tools on design cognition and the creativity of process is an important area of research, both for design disciplines, software engineering and cognitive science. Architects use three types of representation media, or tools, in the design process: paper-and-pencil, physical models and computers. Computer aided design (CAD) software is a piece of technology, which if used as a tool, is viewed with scepticism by some who see it as a hindrance to design, and with optimism by others who perceive it as an aid to design. Unfortunately, claims on CAD’s ability, to enhance or hinder, the creative decision-making process of designers are often contradictory, largely subjective, lack theoretical underpinning, fail to provide any operational definition for creativity and/or its measures and are largely based on anecdotal rather than empirical evidence. For example, Rauhala [92] has seriously questioned the role of computers as a creative design partner in decision making. Two issues were highlighted by this paper: the inability of the computer to generate new design ideas and its lack of capacity to act as a ‘creative adviser’. Yet, Rauhala provides little insights onto what a ‘creative adviser’ means in terms of design nor does it associate creativity with any design traits. Also the paper puts forward little, which can help in ‘measuring’ creativity either as a ‘process’ or as a ‘product’. Rauhala mainly focused on sketching, and the text was largely driven by a romantic and subjective belief that ‘sketching should remain the last fortress resisting the computerization of design’. More, Rauhala [92] went on to suggest that the thought of using computers to generate creative associations in design is not feasible. With little empirical evidence presented to support these generalisations, one has to question their validity. Additionally, there is much more to design than just sketching and the literature provides little empirical evidence in a form of researches that correlate sketching with ideation fluency or ideation variety, two very important indicators for measuring creativity reported in the literature. Along a similar theme of non-empirical ‘generalisation’

from a personal opinion, is that of Lawson [52] who echoed Rauhala's message with a generalised assertion: 'CAD to be some ways short of supporting true creativity'. The 'relative merits' of searching for generalisation, which can synthesize into an educational model, rather than investigations focused on 'single events' has been seriously criticised by Bassey. [9] He suggested, educational practice should benefit from educational research and that the virtue of studying single events 'lies not in the extent to which it can be generalised, but in the extent to which a teacher reading it can relate it to his own teaching.' [9]

Furthermore, recent advances in software engineering have stimulated developments of new types of software, which are generative and in turn more relevant to design and ideation. For example, recent visual programming CAD tools such as Grasshopper [104], are generative in that they use 'parameters' and 'components' linked through 'associations' (input-output) to create not only a single design but a multitude of variants. This design methodology will encourage the creation of multiple design ideas, a conception called ideation 'fluency' in creativity research. The manipulation of 'parameter' values, to create design variants offers designers a working method, which is focused on procedures rather than generating a single geometry for a single design layout. [35]

Additionally, Peters argues modern digital tools have enabled architects nowadays to explore 'a range of design options that previous generations could only dream of'. [84] He views mathematics 'as the language of form and pattern, of science and computers', and suggests 'it's maths that has put these tools at their disposal — it has certainly paid back its due.' [84]

In contrast to Lawson, Wang, Liu and Wang [118] made a positive case for CAD for being a rich source for design ideation, a precursor to creativity. They introduced a creative method to support computer aided architectural design, which was based on: 'shape grammar' and space-surface equations. They advanced a computer programme that can generate building forms, building layouts and building components such as 'domes' from fractals and then compiled a data-base that encompassed a combination of all these design elements. They stated that the 'database model' can help designers in two ways: first as an aid to overcome design fixation which, among other things, causes a lack of stimulus and second as a knowledge-based system for design. [118]

Further literature reviews revealed positive applications of parametric modelling and genetic algorithms in the conceptual architectural design phase both in education and practice, see Turrin, Buelow and Stouffs. [114] Proposals for a generative CAD method for design exploration were also made and reported by Krish [51], which aimed at generating solutions to multi-dimensional design problems where significant performance figures cannot be calculated. [51]

Conflicting views on the design-tool relationship were also reported in other design disciplines. For example, in graphic design Schenk [101] points out to the findings from her research programme and concludes, graphic designers have listed three areas where computers can be deployed effectively: design development, fine tuning of design ideas, presentation/drawing automation. Contrary to this, are findings from Stones [109] who, after an empirical experiment, hinted that paper-based sketching was more effective in generating more design solutions than digital tools and also more valuable 'in supporting one particular synthesis strategy'. The task given to the subjects was simple, thus unrepresentative to real life design problems. Very little cognitive load was involved in problem solving as subjects were asked 'to eloquently combine the letter E with the number 6', a problem essentially simple that it does not require the use of a computer. The cognitive complexity required for designing a building is generally big since function, form,

performance and aesthetics all have to be simultaneously considered. The tools used in this study, Photoshop 7 and Macromedia Flash, do not fall within the main stream of CAD tools in that both cannot deal with three-dimensional modelling of designs. Also, the whole experiment was aimed at the 'graphical' manipulation of two objects, an activity can hardly be classified as design. More importantly, there was little reported on comparing the 'creativity' of graphical synthesis and the 'quality' of solutions generated from both paper and pencil and the software.

Tool neutrality or passivity in terms of their impact on design outcome (and by implication on creativity) is another issue of tool-design relationship. The inherit logic behind this assumption is that a tool cannot push the designer to think in a particular way and in turn it cannot determine the nature of design outcome. Yet, one could argue that something like deploying a CAD software as a tool in design can be considered as an extension to the mind and also to other senses. Therefore, the whole gamut of 'design-tool' relationship becomes far more complicated than just a master-slave scenario where the designer forces the tool to do what they want. Sometimes the tool's strength or weakness in modelling can push the designer to think about design in a very specific way. To fully understand the relationship between 'design' and the 'tool', there is a need to examine tools from two perspectives. The first, a broader philosophical perspective, considers tools as part of 'technology' which historically has produced a significant impact on society. The second, views tools as extensions to the senses and the mind and by implication they will impact the design behaviour. The paper considers issues surrounding notions of tools for design communication, tools as an architectural media, tools as working methods and the purported passivity of tools-as-technology, all as being important themes which require both detailed and rigorous exploration.

In summary, the views held by researchers on computer enhanced creativity seem to be polemic in nature, with 'CAD as a tool' concept oscillating between two extremes: from CAD being neutral or having a 'passive' or little impact on design creativity to it being an 'active' parameter, an essential ingredient for design creativity. This is the context of the research problem this review paper aims to investigate.

2 Systematic review and Meta-analysis

In order to arrange knowledge into a functional and reliable format, the critical assessment and synthesis of research outcomes in 'a systematic manner' began in its first recognized shape in 1975 under the term 'meta-analysis', a phrase attributed to Glass [31] who jointly with Smith performed syntheses in the areas of psychotherapy. [104] They analysed the results from 400 controlled appraisals of psychotherapy and counselling and presented a compelling evidence that psychotherapy is effective. [104] The research procedure involved the use of a typical 'search procedure' to identify 1000 documents from: 'psychological abstracts, dissertation abstracts, and branching off of bibliographies of the documents themselves.' [104] The list documents located was whittled down to approximately 500 which were judged to be appropriate for inclusion in the study. Further screening cut down the list to 375 studies which were fully analysed. In order to be selected, 'a study had to have at least one therapy treatment group compared to an untreated group or to a different therapy group.' [104]

However, the idea of collating 'evidence' from systematic reviews and the emphasis on methodological procedures were largely due to appeals from the 'evidence movement'. [5]

In a meta-analysis of studies on class size and achievement, Glass and Smith [31] highlighted several pitfalls of reviews, namely:

- i literature searches were 'haphazard and often overly selective'; as a rule, dissertations and substantial archives of pertinent data were precluded,
- ii reviews were characteristically 'narrative and discursive'; without deploying quantitative methods of examining the studies the 'multiplicity of findings cannot be absorbed',
- iii reviewers that tried the quantitative methods of integrating the results made quite a few errors with regards to interpretations of statistical significance of differences and they also lacked adequately 'sophisticated [statistical] techniques of integrating results.'

Askie and Offringa [5] suggest that the main motives behind commencing systematic reviews and meta-analyses are to 'minimize bias and to maximize data by collating all the relevant, available evidence on a particular topic [and] a number of key methodological conditions need to be met when undertaking these types of analysis.'

According to Tseng et al. [113] a systematic review revolves around establishing 'evidence' from the synthesis of the medical literature on an individual clinical issue using precise methods to perform a 'comprehensive literature search, identify and select eligible studies, critically appraise their methods, and judiciously summarize the results considering how they vary with study characteristics.' When the methodology involves statistical concepts, i.e. a meta-analysis, reviewers can introduce greater precision from 'a pooled estimate', which will apply more widely than the individual studies. 'The quality of the underlying studies, the consistency of results across studies and the precision of the pooled estimate can considerably affect the strength of inference from systematic reviews.' [113]

On evidence-based simulation practice, Doolen argues that understanding the procedures used for different types of reviews can bring 'clarity to the quality and usefulness of a review.' [22] Furthermore, the author classifies reviews into 3 categories: systematic, meta-analysis and integrative. Systematic reviews congregate evidence that resolves a particular clinical problem. 'If quantitative and qualitative evidence are collected, this is termed as a mixed-method systematic review. Similarly, if the studies within a systematic review are similar in design, a statistical procedure or a meta-analysis can be conducted to calculate an overall effect size of the intervention(s).' [22]

Hansen and Rieper [39] indicate that the idea of systematic reviews started in medicine then moved into other disciplines, and as a result, a number of international as well as national 'second-order knowledge'-producing societies were founded. They define a systematic review is as 'a synthesis of results of existing evaluations and research projects produced with the purpose of clarifying whether a given intervention works.' [39] The 'knowledge' created through systematic reviews is termed 'evidence'. The objective of constructing evidence in the form of systematic reviews is 'to promote well-informed decisions about policy initiatives and professional practice.' [39] Furthermore, systematic reviews became the research theme, which led to the establishment of a number of specialized organizations such as the Cochrane and Campbell Collaborations and 'the evidence movement'.

According to the Cochrane Collaboration, a systematic review 'attempts to collate all empirical evidence that fits pre-specified eligibility criteria in order to answer a specific research question. It uses explicit, systematic methods that are selected with a view to minimizing bias, thus providing more reliable findings from which conclusions can be drawn and decisions made. [19] Many systematic reviews contain meta-analyses, which according to the EPPI Centre, is the use of 'statistical methods to summarize the results of independent studies.' [25] The main physiognomies of a systematic review are [42]:

- i a precise and clear set of objectives with established eligibility criteria for inclusion of studies
- ii a definite, 'reproducible methodology'
- iii a systematic search to ascertain which studies would fulfil the eligibility criteria

- iv a validity appraisal of the outcomes of the included studies through the assessment of risk of bias (RoB)
- v a methodical demonstration, and synthesis, of the features and findings of the included studies

Oliveras, Losilla and Vives [81] introduce two terms in assessing the quality of systematic reviews: methodological quality (MQ) or risk of bias (RoB). They used electronic databases and randomly chose 90 systematic review or meta-analysis studies and found that only 46 reviews (51%) implemented a recognised assessment of the RoB of primary studies and only 17 reviews (19%) connected the results of quality assessment with the outcomes of the review. They concluded: i) there is an absence of guidance on how to include the RoB assessment in the outcomes of systematic reviews and meta-analyses; ii) MQ is played down in systematic reviews and meta-analyses in health psychology. [81]

Kastner et al. [49] advocate the term ‘knowledge synthesis’ which implies a summary of all relevant studies on a specific question and argue that it can improve the ‘understanding of inconsistencies in diverse evidence and can define future research agendas.’ [49]

On conducting literature search for a systematic review, Bartels [8] outlines 8 steps. These are: identification and definition of the research problem, defining a search strategy, choosing the right bibliographic databases, performing a search, identifying suitable references from those that have been retrieved, assess the outcome from the search, if the search was unsatisfactory reformat the search strategy or choose other databases/search tools, and do again steps 2–6, if needed. [8]

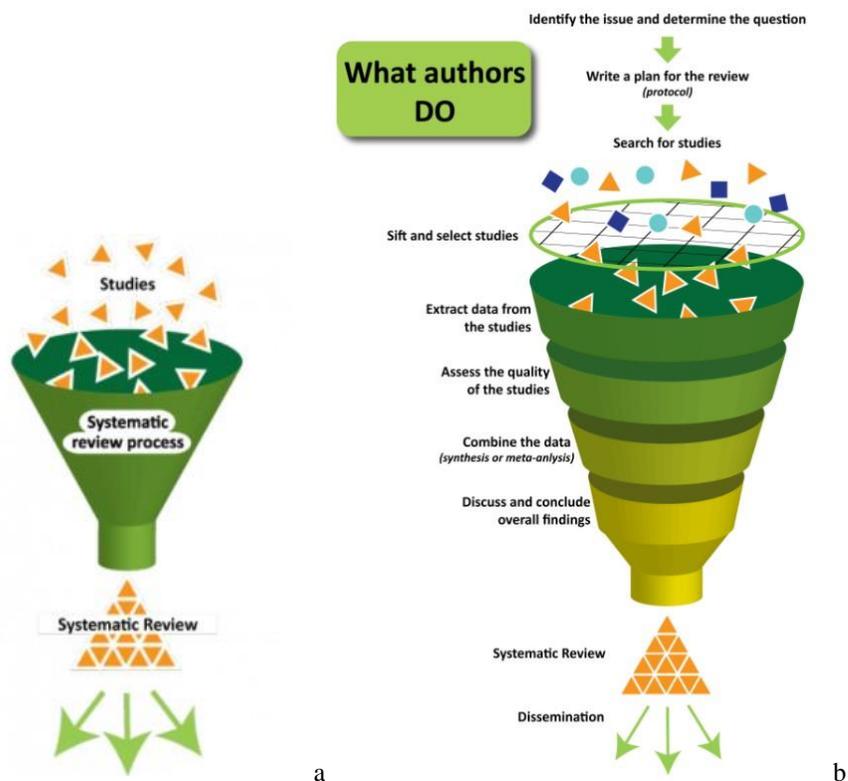


Figure 1: a) The Concept of a Systematic Review, b) Established Methodology for Systematic Reviews [19] [adapted from: <http://cccr.org/what-are-systematic-reviews>]

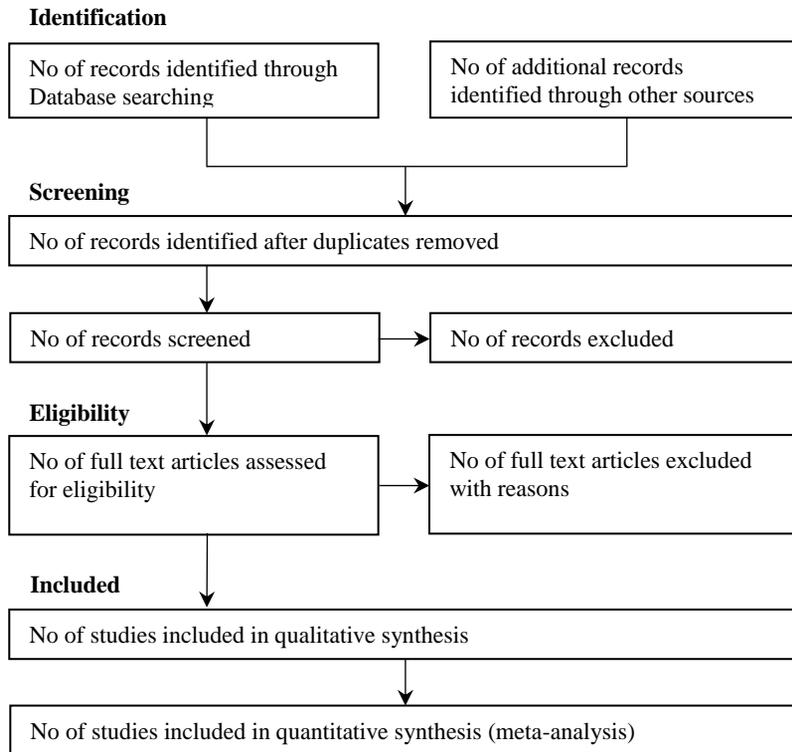


Figure 2: Flow of information through the different phases of a systematic review [53]

Whittemore and Jang [117] classify established knowledge synthesis methods into two categories. The first comprises the systematic review, meta-analysis, qualitative synthesis, and integrative review. More recently, a second category of methods, which encompasses mixed-studies reviews, scoping reviews, reviews that examine efficacy and generalisability (i.e., RE-AIM review), and reviews of systematic reviews (i.e., umbrella reviews) have been advised. Additionally, these methods and guidelines for describing reviews outcome besides individual studies 'continue to be revised to enhance the rigor of knowledge synthesis methods and the applicability and transparency of findings to practice and policy.' [112]

Cochrane Collaboration [19], on their website, has produced a visual diagram to describe the concept and the procedure of conducting systematic reviews, Figure 1: a) and b).

The flow of information through the various stages of a systematic review, adapted from Liberati et al. [53], is presented in Figure 2.

The methodology in Figure 2 was followed by this research to conduct systematic searches for literature in design computation using various online search engines, library databases and printed books. Phrases such as 'computers and creativity', 'statistical measures for creativity', 'complexity of form and creativity', 'tools and causality', 'impact of tools on design outcome' were used sometimes with Boolean operations such 'AND', 'NOT', 'OR', 'NEAR', etc. For quantitative and statistical papers ScienceDirect and PubMed produced searches that closely matched the phrases used. For qualitative reviews library databases on books

and chapters in books produced relevant sources which closely matched the search criteria. In total 269 documents were unearthed and downloaded from the search engines. After an initial screening of the 269 documents, 79 researches were excluded based on various criteria, outlined in Figure 3. After this initial screening the researches were whittled down further to 190 documents. Further review and application of inclusion measures resulted in 122 final documents used directly as references and 6 additional documents, not referenced but deemed useful as a bibliographic material for statistics.

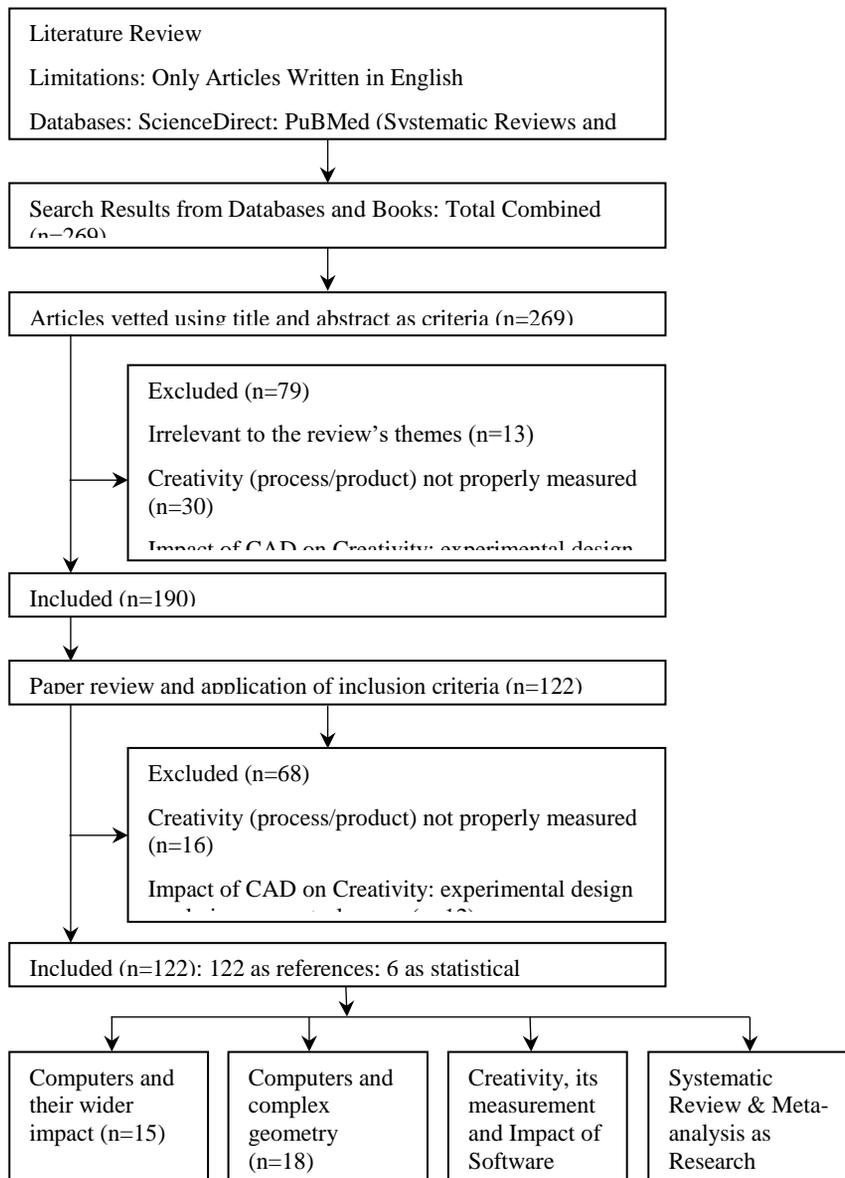


Figure 3: Flow diagram showing the number of studies selected (n) and how they were selected [based on PRISMA (preferred reporting items for systematic reviews and meta-analyses) [53]

3 Statistical analysis of search engines

The statistical package for social sciences (SPSS) was used to code the researches against engine type which in turn was associated with the relevance of 'title and abstract' to the search criteria. The aim was to establish whether there was a relationship that is statistically significant between the type of the 'search engine' and the relevance of 'title and abstract' given by the search engine to the search criteria.

Table 1 shows the total number of papers accepted/rejected after screening using the established selection criteria. The ScienceDirect search results produced more research hits than PubMed or library databases.

Type of Serach Engine * Relevant: Title & Abstract Crosstabulation

			Relevant: Title & Abstract		Total
			no	yes	
Type of Serach Engine	ScienceDirect	Count	28	73	101
		Expected Count	36.1	64.9	101.0
	PubMed	Count	28	27	55
		Expected Count	19.7	35.3	55.0
	Books (Libraries DataBase)	Count	12	22	34
		Expected Count	12.2	21.8	34.0
Total	Count	68	122	190	
	Expected Count	68.0	122.0	190.0	

Table 1: Number of papers accepted/rejected by search engine.

The research proceeded to first compute if the mathematical difference (Table 1) between search engines was statistically significant to reject the null hypothesis of 'no statistical difference' and second whether this difference was due to statistical chance rather than the result of real 'association' between 'search engines' and 'search outcome', the latter determined by the inclusion criteria.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	8.335 ^a	2	.015
Likelihood Ratio	8.214	2	.016
Linear-by-Linear Association	2.474	1	.116
N of Valid Cases	190		

a. 0 cells (.0%) have expected count less than 5. The minimum expected count is 12.17.

Table 2: Pearson Chi Square test with Asymptotic Significance

Table 2 shows a level of significance which is <0.05 ; this means that we should reject the null hypothesis of no statistical difference and confirm the target hypothesis, i.e. the existence 'of statistical difference'. Also, the value of Pearson Chi-Square of 8.335 was much higher than the recommended critical value of (Chi-Square=5.99, $df=2$, P (significance)=0.05) which is another strong indicator for the rejection of the null hypothesis.

Correlations

		Relevant: Title & Abstract	Type of Serach Engine
Relevant: Title & Abstract	Pearson Correlation	1	.231**
	Sig. (2-tailed)		.004
	N	156	156
Type of Serach Engine	Pearson Correlation	.231**	1
	Sig. (2-tailed)	.004	
	N	156	156

** Correlation is significant at the 0.01 level (2-tailed).

Table 3: Pearson correlation between title/abstract relevance vs. search engine

Furthermore, this research deployed Person point-biserial correlation technique to calculate the association/correlation between the type of search engine (ScienceDirect and PubMed) and the relevance of resultant ‘title/abstract’ to search criteria. Table 3 reveals a high correlation coefficient of 0.231 at a 0.01 level significance, which denotes a 99% confidence and only 1% chance in the correlation between search engine and search outcome in terms of research papers revealed by each of the three engines.

Directional Measures

			Value	Asymptotic Standard Error ^a	Approximate T ^b	Approximate Significance
Nominal by Nominal	Lambda	Symmetric	.006	.047	.135	.893
		Type of Serach Engine Dependent	.000	.000	. ^c	. ^c
		Relevant: Title & Abstract Dependent	.015	.108	.135	.893
	Goodman and Kruskal tau	Type of Serach Engine Dependent	.027	.019		.006 ^d
		Relevant: Title & Abstract Dependent	.044	.030		.016 ^d
		Uncertainty Coefficient	Symmetric	.026	.018	1.435
	Type of Serach Engine Dependent		.022	.015	1.435	.016 ^e
	Relevant: Title & Abstract Dependent		.033	.023	1.435	.016 ^e

- a. Not assuming the null hypothesis.
- b. Using the asymptotic standard error assuming the null hypothesis.
- c. Cannot be computed because the asymptotic standard error equals zero.
- d. Based on chi-square approximation
- e. Likelihood ratio chi-square probability.

Table 4: Directional measures statistics: Lambda, Goodman and Kruskal tau and Uncertainty Coefficient

Directional measures statistics calculates the reduction of error in the prediction of relevant abstract/title from the type of search engine. Goodman and Kruskal tau specify error as the ‘misclassification’ of a single literature item found by any of the search engines. The tau value of 0.27 with search engine dependent means that there is a 2.7% drop in the miscalculation which is very small. This small value in turn infers that the relevance of ‘title/abstract’ to search criteria was strongly associated with search engine.

Additionally, the statistics computed a value for odds-ratio which is dependent on the type of search engine. The question here is: how strong is the probability that ScienceDirect will yield more relevant researches than PubMed? The results, Table 5, confirm that ScienceDirect is 1.472 times more likely to produce relevant abstract/title than PubMed. This implies that ScienceDirect is highly likely to produce more hits in terms of research papers that are relevant to the search criteria than PubMed.

Risk Estimate

	Value	95% Confidence Interval	
		Lower	Upper
Odds Ratio for Type of Serach Engine (ScienceDirect / PubMed)	.370	.186	.734
For cohort Relevant: Title & Abstract = no	.545	.362	.819
For cohort Relevant: Title & Abstract = yes	1.472	1.096	1.977
N of Valid Cases	156		

Table 5: Odds ratio with confidence interval for type of search engine

To extrapolate on the impact of search engines on search outcomes beyond the n=190 of valid cases this research deployed the Kruskal-Wallis test with the Monte Carlo simulation procedures. The Monte Carlo simulation on 10000 samples produced a significance of 0.015 (<0.05), at a 99% confidence interval, which is very close to that produced by the Kruskal-Wallis test on n=190 cases generated by the three search engines used in this research.

Kruskal-Wallis Test Statistics^{a,b}

		Relevant: Title & Abstract
Chi-Square		8.291
df		2
Asymp. Sig.		.016
Monte Carlo Sig.	Sig.	.015 ^c
	99% Confidence Interval	
	Lower Bound	.012
	Upper Bound	.018

- a. Kruskal Wallis Test
- b. Grouping Variable: Type of Serach Engine
- c. Based on 10000 sampled tables with starting seed 2000000.

Table 6: Kruskal-Wallis test with Monte Carlo Simulation

The researches from the 3 search engines that had fulfilled the inclusion criteria were subsequently classified into various themes which formulate the backbone of this systematic review. The main thesis of this paper is split into 2 intellectual domains which out-with the research questions are presented in a diagrammatic format, for better comprehension, in Figure 4.

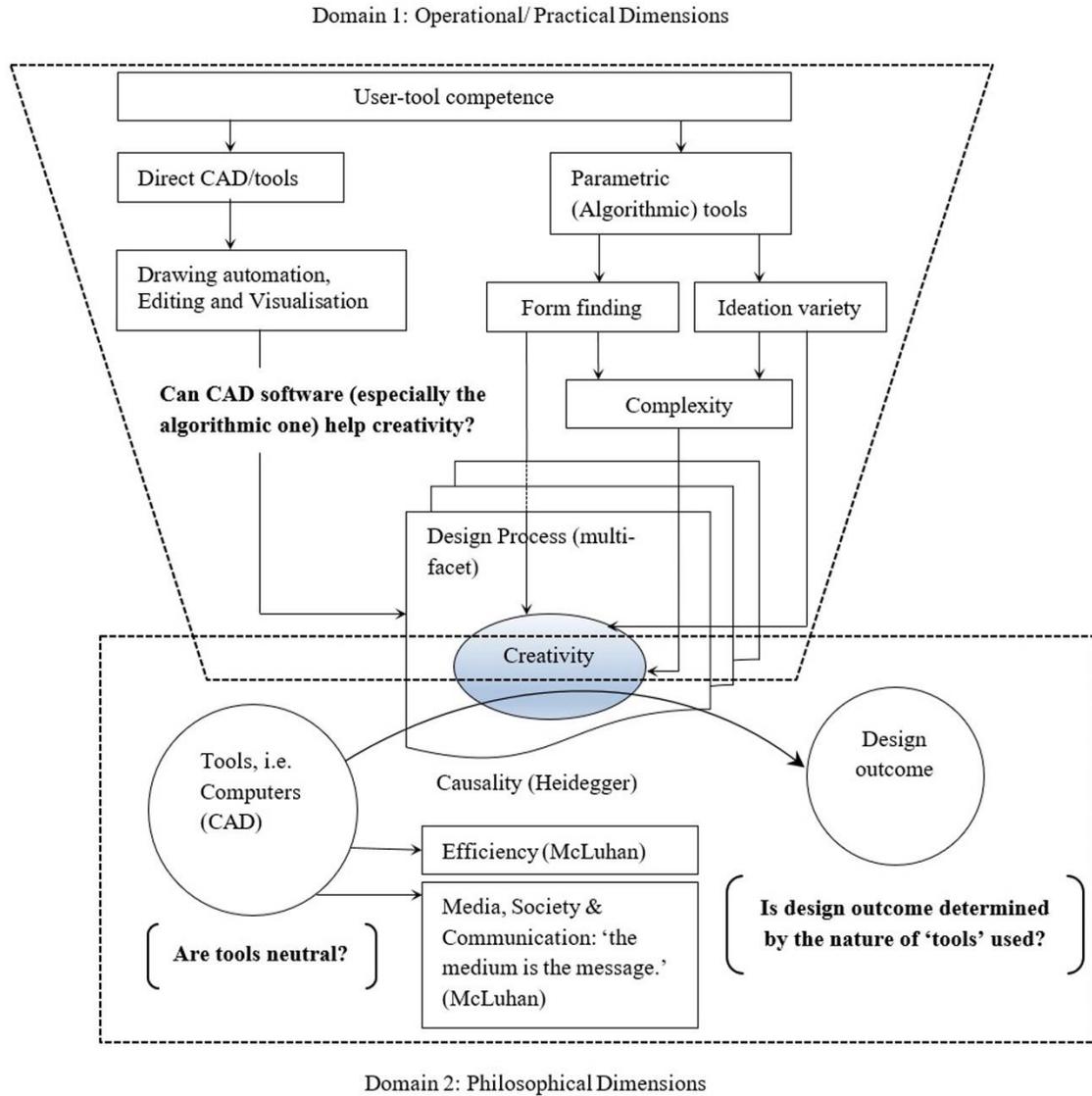


Figure 4: A diagrammatic abstract of the main themes covered by this paper

4 Computers and their wider impact

Most studies that examine computers in design regard them as tools; they do not consider computers from a broad perspective as a wider societal phenomenon. Yet computers' spectrum of influence is wider than just design domains because the notion of computers as a 'media', a means for communication, can affect both society and individuals_ including designers. A case in point is the Internet and its impact on society's perception of time. Similarly, our perception of distance has changed because of the aeroplane. Lee and Whitley [54] note that information technology is 'transforming time, the way time is perceived, used, managed, and disciplined'. Meanwhile, Green [36] avers that mobile computing and telecommunications

technologies hold the potential to transform everyday time and space, as well as changes to the rhythm of social institutions. The impact of information technology on the use of physical space by individual and organisations was examined by Lucas [59] who predicted that the emergence of virtual organisations and telecommuting will reduce the future demand for office space.

McLuhan and Fiore [66] maintain that the issue that moulds societies is the type and character of the media itself rather than the message that the media transmits, i.e. 'content of communication'. They highlight the difficulty of understanding societal changes without knowing the 'workings of media'. [66] Linking tools to efficiency, McLuhan remarked, 'our age of anxiety is, in great part, the result of trying to do today's job with yesterday's tools- with yesterday's concepts'. [67] McLuhan's argument on the impact of tools seems to echo the notion that the type of design media one works with can influence their conception of design problems and consequently may determine the nature of design output. It is also obvious that computers can operate at several domains and not just on the 'single' context of CAD to aid drawing efficiency, form optimisation, accuracy and cognition.

On the impact of computers on the production of 'creative' art work, Alsop argues that computers offer artists external knowledge which could enhance their imagination which may be hindered by their own internal knowledge. [2] He remarks 'try imagining something you don't know'. But the diversity computing offers may address this problem. For the creative artist, computers supply three basic tools: 'access to information, software, and new ways to interact.' [2] In the arts, Alsop argues that, computers have a range of applications, depending on the type of software package, which stretch from executing the 'artist's ideas to creating ideas.' [2]

On the level of individuals, Failla and Bagnara [27] explored the impact of technology on decision making and problems solving. They stated that technologies associated with individual-decision making are devoted to the appraisal of alternatives in problem solving. Furthermore, they concluded that the aim of using 'tools', such as spread sheets, data basis and statistical programmes, by the decision maker, is to make the decision-making process faster and more reliable.

The link between design working method and the nature of design outcome has been examined. Design representation typologies like words, drawings, and models (physical/digital) can have a significant impact on architectural thought; more 'distinguished thought processes will lead to more distinguished forms' which will sequentially generate more unique architectural expressions. [44] Additionally, design working methods and thought processes are linked; one gets more design 'insights' if they can competently move from one method to another. [44] Similarly, the ability of a designer to conceive ideas and produce solutions correlates with the power of 'tools' in their disposal, see Heath. [40] Furthermore, limitations in the use of a particular working method can hinder thinking and will be exposed as weaknesses of the design. If a design subject cannot draw freely, either with paper-and-pencil or CAD, they will be limited in what they can produce in design; certainly, they will be constrained by their inability to fully deploy the power of representation. They will become 'the victim of analogue take-over'. [44] Ideally, digital media can be deployed to add another dimension to architectural representation alongside traditional methods (physical models and drawings). Their potential for producing accurate three-dimensional modelling of geometry, their drawing efficiency and their power of visualisation and simulation of environments is well documented. In fact, such is the impact of technology and process on architecture that some of the complexity of 'form' can only be resolved effectively with the use of CAD in modelling as well as the manufacturing process. Novak suggests that the utmost 'thought-provoking and mentally taxing forms of

architecture' being invented around the world nowadays could not have been envisioned without the aid of the computer. [80]

5 The computer: A philosophical context

At one level, the computer is a 'technology' which offers designers a way of seeing, thinking and problem solving that is different from paper and pencil. On another level, technology is also a human activity, has intellectual context and is a means to an end. This section briefly examines the essence of 'technology' from a philosophical standpoint because, technology's problems and those of philosophy, are inseparable according to Dewey. [41] In the literature, two orders for technology were identified by Mitcham. [71] The narrow order, adopted by engineers and designers, views technology as the realm of tools, machines and electrical devices and concerns using technology for innovation and better performance. The broad order, adopted by philosophers of technology, is not only concerned with the making of material artefacts but more importantly with their 'intellectual and social contexts'. [71] Furthermore, Mitcham and Mackey [72] identified three philosophical approaches to analyse technology. The first two approaches examine technology as a problem of epistemology and as an anthropological position regarding the nature of human life. The third views technology as 'the defining characteristics of thought and action in modern society'. Are technologies 'passive' things that can do nothing by themselves, or do they affect the 'very ways we act, perceive and understand'? [72] There appears to be two views on this. The first, named 'social determinism', asserts that human social and political factors are dominant over the technological ones- the latter are viewed as background factors. The second, 'technological determinism', avows that development of a technology itself has always opened up many possibilities that have greatly influenced the future directions for the society at large. [72]

Furthermore, Heidegger's lecture, at the Bavarian Academy of Fine Arts on the theme of 'the arts in the age of technology', establishes a firm 'relationship' between human existence and the 'essence' of technology, maintains Gorner. [34] Significantly, Heidegger describes the 'essence' of technology in terms such as: means to an end, a human activity and as an 'instrument'. [50] On technology as an instrument, Heidegger suggests 'wherever ends are pursued, and means are employed, wherever instrumentality reigns, there reigns causality'. [50] Furthermore, he identifies causality as being: material, shape/form, subjective will of maker, and functional. These four causes, according to Heidegger, are responsible for bringing 'something into appearance' or 'revealing'. Heidegger, then poses the question: what has the essence of technology to do with 'revealing'? His answer suggests that 'bringing forth [revealing] gathers within itself the four mode of causality and rules them throughout' and concludes: 'technology is therefore no mere means... technology is a way of revealing' and that 'the possibility of all productive manufacturing lies in revealing'. [50] Within the context of using technology, i.e. computers, in architectural design, Heidegger's message, if anything, elevates the computer from being a mere drawing tool to a design determinant, from a controlled object to a controlling object. The notion held by many design scholars that computers are passive design tools or at best techniques, thus, can be challenged if we were to use Heidegger's message as a measure. Heidegger's thesis also implies that computers are more than just a means to produce design drawings; they can be a device for revealing and 'bringing forth' designs. If we accept the 'tool-outcome' relationship, taking on board Heidegger's thesis on causality, it seems plausible to deduce that a building produced though the computer will somehow have a notion of 'revealing', through form or shape, which is different from that generated by conventional sketching (paper-pencil). It could also be that the computer's

way of revealing is such that it favours complex and un-linear forms. Figure 5 represents a visual summary for the relationship between tools and the idea of bringing forth.

Under the heading 'technology is not neutral', Steele [107] refers to Albert Borgmann and Joseph Weizenbaum and their call for a more appraised approach to this technology, concentrating on its 'power to usurp our ability to act independently, as well as the tendency to substitute information for reality.' [107] Additionally, both stress that technology and tools are far from being passive in that they reformat and remould the tasks they are deployed for, the users' perception and cognition and the message and the 'meaning behind the tasks'. [107]

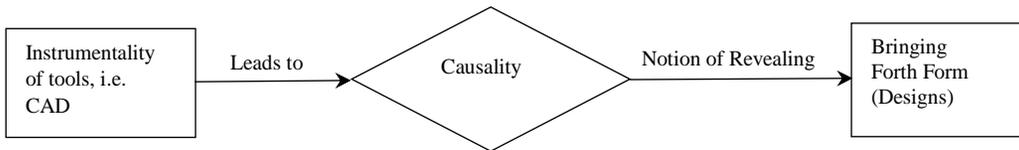


Figure 5: The computer as a tool for 'revealing' form (based on Heidegger's thesis)

6 Computers and complex geometry

According to literature, the exploration of complex non-linear geometry is an area where the computer (CAD) can make a difference to the design process. In architectural education, there is a belief that CAD, if used as a design medium for visualizing objects in three dimensions, can improve students' spatial ability including the conception of complex geometry. The addition of parametric and generative tools will offer experienced designers in general and novice designers such as students in particular, exciting opportunities to generate design variants and complex forms.

Examining the relationship between geometry form and complexity, Peters and Whitehead [85] argue that in traditional design processes notions of proportion and harmony coupled with the accuracy needed to 'coordinate delivery by large numbers of people under a legal contract, could both be specified within the same system.' The insinuation, according to both, is that creativity and the drive towards generating aesthetically beautiful forms will not be conceded because of adopting this rationale. This, according to both, is now being contested by the use of 'digital technology to produce free-form buildings which, by transcending the limitations of Euclidean geometry, can deliver an aesthetic that appears more organic but which can also achieve higher levels of performance.' [85]

Referring to the Stata Centre at MIT, designed by Frank Gehry and completed in 2004, as being 'both large and complex', Mitchell [73] defines complexity as the ratio between the number of added elements in design to the number of added elements in construction. So, if both design content and construction content are increased the outcome in terms of complexity will increase. Therefore, a six sided polygon will have a higher design and construction content than a rectangular shape and by implication it can be described as more complex.

The architectural practice also witnessed significant changes in working methods as the design process became more reliant on the use of generative tools with many practices opting to create computation units for advanced geometry within. [23] However, the picture in practice is split, though, with some still using CAD software as an efficient tool for drawing automation and presentations, while others deploy CAD as a medium to inspire novel and complex forms. [120] More, Zellener suggests the 'information revolution' is the real force transmuting both architecture and urban design. Digital technologies, he argues, are altering

‘the nature and the intent of architectural thinking and creativity’, smudging the associations between simulation and reality, data and physicality, between the natural and the synthetic and commanding us into an insecure terrain leading to the production of imaginative and original forms. [120]

Consequently, a new breed of architects appeared; they disassociated themselves with long held traditional beliefs in architecture. This emergent group of architects, Posnratz and Perbellini argue, has broken away from the design principles of the ‘modern movement’ and is working on a ‘different terrain’ defining a new meaning for space through new working methods, producing buildings with a high degree of complexity, and exploring geometries that were previously impossible to pursue. [89] This group also seem to adopt an intellectual position and push for a new frontier in architecture, leaving behind traditional design philosophies and processes.

On computer-based design process, Rahim asserts that contemporary processes rely on modes of thought that are ‘non-deterministic’ and ‘non-static’. [91] Picon [86] opines, the most immediate consequence of the use of computer is without doubt the possibilities it offers to ‘manipulate complex geometries often giving the impression that architecture was entering a new baroque condition.’ Computers are also a useful medium to bridge the gap in our perception between physical and digital reality as they can create an ‘augmented’ reality, where experiences from one type of reality can inform the other. [86]

Examining CAD’s impact on geometry, Penttila and Howard [83] suggest that computers have also ‘resulted in a more complex, curved and free architectural building geometry, which has been enabled by modern CAD-tools.’ Additionally, Novak [74] attributes the conception of advanced and complex architecture to the use of computers in design.

Aish and Hanna maintain that most parametric tools have three forms of representation: diagrammatic data flows of input-output, geometric depictions and text based symbolic depictions. [1] In addition this typology of tools offers great flexibility in terms of use as they allow the designer to experiment and make speculative design decisions that may be consequently modified. ‘Overall parametric design applications based on visual data flow programming data flow are extremely flexible compared to modelling application based on direct manipulation.’ [1]

Loh remarks, initially the use of algorithmic design was deployed to organise spatial assemblies and create complex forms according to scripting lucidity. [56] Current progress in software and input from other fields such as ‘film, aerospace and product engineering, architects are now designing ever more complex geometries to explore unprecedented spatial conditions and relationships.’ [56] Mitchell notes: ‘today, innovative applications of computer-aided design and manufacturing technology are allowing architects to transcend long-standing limits on complexity and, thus, to respond more sensitively and effectively to varied human needs and construction contexts.’ [74]

More on complexity, Mitchell contends, if input a small number of commands and assign quantities to entities in a CAD system is sufficient to produce ‘a great deal of construction content, then the project is of low complexity’. If the number of parameter values needed for an input is large, i.e. when we want to construct and digitally fabricate a multi-sided ‘irregular polygon’, the complexity verges on a hundred percent. ‘Differences in complexity arise because a command given to a computer-aided design system may imply more construction content than immediately meets the eye.’ [74]

However, the counter argument for the computer-complexity relationship is that many buildings with complex geometry such as Gaudi’s Sagrada Familia in Barcelona, were conceived without the computer.

Unfortunately, our understanding of how design cognition is affected by the computer in terms of receiving, processing and manipulating design information regarding complex geometry is insufficient to enable us to deal with this conflict. Yet there are two issues around computers and complexity that have certainty about. Firstly, the frequency at which we are designing complex geometry now is much greater than what happened in the past. Secondly, digital fabrication of complex geometry using the computer has made the construction process of complex buildings more cost effective.

6.1 Computers: Generative tools in design

As stated earlier, the computer in architectural design is seen either as a design 'medium' or a 'tool' with little impact on design thinking. McCullough [64] reflects on the last 20 years of development of computing in architecture and suggests, architecture has rediscovered a programming culture in design. He gives two reasons for this. The first motive is that of digital fabrication and the lure to articulate designs linked to machining processes. Second, form as an expression of 'cultural message' if generated from genetic algorithms then principles of beauty and harmony are coded and programmed with influence from biological systems. [64]

Computation's impact on the rediscovery of architecture, Rocker [94] reasons that to generate architecture from programming codes forced conventional architects to re-asses their design process. She suggests, computation through coding allows architects to generate form and space, both independent of the constraints experienced by traditional architecture. The logical procedures built in CAD programmes and the flexible nature of commands both have a creative potential that until recently has been undervalued in architecture. [94] According to Silver the happy accident in blob architecture of the 1990s has been replaced by a new focus on programming and code writing which promises 'to generate new and unprecedented modes of expression'. [103]

On parametric processes, Freiberger [29] intimates, although parametric modelling started in 1960s, it is only now that architects are taking advantage of its generative power. Parametric models typically embrace the idea of associative geometry through a hierarchical data structure. These associative links between different aspects of form enable designers to modify certain parameters or 'features of a building without having to re-calculate all the other features that are affected by the changes', [29] which gives them the potential to become design tools with enormous power and capability. Hanna and Turner [38] say that generative systems are relatively new but will force a new way in design thinking and the perception of CAD in terms three-dimensional modelling and visualisation. More, they hint that a large percentage of design outputs from generative systems aims at understanding the design methodology of such systems. [38]

Similarly, Zaera-Polo, [119], maintains that new technologies have enabled architects to initiate and progress sophisticated patterning techniques, creating a new aesthetic language of building facades and envelopes which is based on tessellations, smooth surface geometries, material textures and surface layering. The drive toward polygonal tessellations in contemporary envelopes include buildings such as Ravensbourne College, London (2010) and PTW's Beijing Water Cube (2007). Further, he suggests that practices such as Greg Lynn FORM, OMA, UN Studio and others have developed sophisticated and complex patterns on 'different scales of operation'. These patterns can be translated from biology to architecture and this can occur on three levels, see Vincent [115] First, is to copy biological shapes and objects such as leaves, shells and bones directly. Second, is to recognise ways in which problems are solved

in biology and apply similar problem-solving strategies to engineering. Third is to use the method of interrogation that leads to synthesis- a solution to the design problem. [115]

Meanwhile, considering spheres of enablement, computers have allowed us to create new configurations for space and new structures both originating from the parametric manipulation of simple rules and proportional relationships where, according to Bosia, 'complexity is generated by the recursive repetition of simple processes'. [13] Indeed, Scheurer and Stehling concur, complex shapes and geometry 'can only be handled' if digital or parametric tools are not an essential component of architectural design and communication. [102] The conception and the fabrication of complex forms, geometry, shapes and facade patterns would not have been possible if the digital paradigm had not progressed from polygon to NURBS (non-uniform rational B-splines) modellers. This significant digital shift in has overcome the serious limitations of traditional polygon modellers and excelled their modelling performance. Intellectually, the change provides an alternative to the 'orthogonal rigidity' of the Cartesian system, an issue rightly criticised by Gomez and Pelletier for representing a deterministic form of modernistic rationality. [32] The introduction of visual scripting, i.e. Grasshopper [82], has added significant 'parametric' capabilities, an exciting and creative dimension to the design process. Such is the excitement about parametric tools that some go further and predict a 'paradigm' shift in architecture brought about by parametric modelling. These tools, Stavric and Marina hint, will play various roles in the design process, ranging from form finding at the early design stage to the manufacturing of architectural elements. [106] Furthermore, the use of genetic algorithms for the optimisation of building design for energy efficiency is well publicised in the literature, see Znouda et al. [122] Tedeschi argues that the drive toward complexity in building design caused architects to seek 'form finding' approaches that can successfully address the problem of form and shape when dealing with 'indeterminate structures'. [110] Furthermore, citing the work of Gaudi, he maintains that 'form-finding' which started in the 19th century as a design approach was the single most significant reason behind architects beginning to look for working methods other than conventional drawings. [110]

However, some scepticism remains about the use of parametric tools in architecture. Meredith [70] describes the current trend of using parametric tools in architecture as being 'superficial and skin deep' for being focused on complex geometry and production while ignoring the more fundamental socio-cultural dimensions of architectural 'form'.

Another area of CAD which is gaining currency nowadays is that of Building Information Modelling (BIM) and its application in practice to facilitate and progress design projects from conception to completion and to promote work flow through the dynamic exchange of data between various design professionals. Some literature on the use of BIM for refurbishment and retrofit of old buildings in France also exists. Joblot et al. [46] recommends the development of BIM metrics and measurements tools that can be used for renovation projects. [46] The interaction between BIM technology and photogrammetry for scanning existing buildings has also been investigated. [17] Cepurnaitea et al. recommend advancing BIM technology to become a tool to collect information about building geometry, energy consumption/appraisal, and components' attributes. [17] Fadeyi, on the other hand, links BIM to issues of producing sustainable buildings through energy appraisal. [26] Fadeyi also affirms that BIM offers 'a virtual repository that allows easy access to and sharing of information and knowledge in real time.' [26] Najjar et al. [76] investigated and appraised the integration between BIM and life cycle assessment (LCA), introduced and validated a new methodology for BIM-LCA integration and concluded that 'BIM-LCA integration empowers sustainable design and decision-making process.' [76] Soust-Verdaguer, Llatas, García-Martínez [105] examined BIM-based LCA focused researches, and analysed their methods of BIM-LCA integration,

placing special emphasis on the manner of how BIM influences the simplification of data input, and the optimization of output data when the LCA procedures are deployed in buildings. The paper confirmed that viability to cultivating methods founded on BIM models is a viable option to structure building information deployed for the purpose of approximating energy consumption impacts using LCA as criteria. [101] However despite that the literature on BIM is wide, deep and varied there is very little, which is written, that investigates the impact of BIM as a CAD design tool on design cognition and or design creativity.

Finally, to address some of the aforementioned issues the author developed a generative algorithm (Appendix 1) in Grasshopper to create a doubly ruled surface from a single catenary curve. This algorithmic process shows that the surface is generated out of relationships (represented by thin lines) between 'components' and 'parameters'. There is very little visual resemblance between the abstract system of buttons and wires in appendix 1 and the resultant object in appendix 2. A novice designer who is used to drawing objects directly on the screen may find such a system difficult to use at the early design stage. On the other hand, the flexibility of this parametric system can offer many advantages. The division of the surface can be dynamically changed in both directions, using the slider (appendix 1) to optimise the design aesthetically and structurally or create a volume and variety of forms. If the height or the width of the catenary curve is modified, then a new surface will be introduced. Any change in a single parameter will introduce a change in other components and consequently will transform the whole system generating design variants which is called 'fluency' of ideas in creativity research. This generative process can be useful for the articulation of architectural elements and can also facilitate their digital fabrication.

7 Creativity, its measurement and Impact of Software

A creative idea is said to have two properties: originality and being appropriate to the context in which it exists, i.e. useful, whereas creative productions, according to Martindale, are seen as 'novel combinations of pre-existing mental elements'. [63] On its own and sometimes allied with originality, creativity has always featured in architectural design definitions. The design process, in Zeisel's view, can be described as an embodiment of many intangible elements including creativity, intuition and imagination, which are critical to quality. [121]

The literature on creativity is wide, deep and varied with emphasis on four domains: process, product, person and context (environment). Additionally, the nature of creativity studies has been classified into five groupings: 'experimental, psychometric, historiometric, biometric and biographical, see Plucker and Renzulli. [87]

Creativity's link to personality has been systematically explored; an example is the ground-breaking effort of Barron [6]. MacKinnon also linked the creativity of three groups of architects to 'variance' in personality traits such as their preference of conformity to internal or external standards of architectural excellence. [61] Using the Barron-Welsh Art scale, Barron and Welsh dispensed a 400-item test figure preference to a sample of artists and non-artists. Using the statistical technique of factor analysis non-artists were found to prefer 'simple, regularly predictable, following some cardinal principle which can be educed at a glance' whereas artists were noticed to desire figures that are 'complex, irregular, whimsical, freehand rather than ruled'. Artists called them unforced and natural. [7]

Intuition, the instantaneous apprehension of a problem, when considered as a method involves three dissimilar items according to Deleuze, cited by Nayak. [79] First, intuition involves the initiation and articulation of problems; second, 'the discovery of genuine differences in kind; third, the apprehension of

duration.’ [79] Gough [35] argues that for a personality to be labelled as creative it has to be forceful and intuitive. Intuition is also associated with duration and time by Bergson [10] who suggests that intuition is instantaneous. According to Bergson: ‘to think intuitively is to think in duration. Intelligence starts ordinarily from the immobile and reconstructs movement as best it can with immobility in juxtaposition.’ Movement initiates intuition and creates a contextual reality for it whereas ‘immobility’ is ‘only an abstract moment, a snapshot taken by our mind, of a mobility.’ [10] Westcott defines intuition as a style of thought that can be usefully deployed to make inferences, judgments and projections, which are very likely to be accurate, from a limited amount of information. [115] Intuition, the instantaneous apprehension of a problem, is connected to creative traits by Policastro, who defined creative intuition as a ‘vague, anticipatory perception that orients creative work in a promising direction’. [88]

The measurement of creativity through validated and confirmed test has attracted a great deal of research effort. One of the most validated tests is the RAT (remote association test), a 30-item word association test where each item consists of three ‘known’ stimulus words and the subject is required to find a fourth word, which could provide an associative link between the three unrelated ones. [68] In addition, Mednic [69], the originator of RAT later on examined the correlation between ‘rated originality’ and RAT scores in 21 design students and found a strong coefficient value of 0.70, between faculty rating and students’ RAT marks. A further support for using RAT came from McFarline and Blascovich [65] who, after three large case studies, recommended the use of RAT ‘whenever the manipulation of performance and an alternative to heavy deception are required’. However, Datta [20] doubted the validity of RAT for architects and engineers. Datta noted Mednic’s findings regarding the weak correlation coefficient of 0.31, which he found between rated originality and RAT scores of 40 distinguished architects, a result, which was in total agreement with her own empirical study with 21 engineers. [20] Each engineer was jointly rated for ‘creativity’ by their immediate supervisor and their section manager and this was correlated with their individual RAT score; a correlation coefficient of +0.31 was computed, which was statistically not significant at the 0.05 level.

According to Sadler-Smith, Wallas, there are four important stages, recognised in the process of creativity: ‘preparation, incubation, illumination (and its accompaniments), and verification.’ [99] Torrance identified four main parameters for creativity: fluency (volume of ideas); flexibility (variety of ideas); originality (rarity of ideas); elaboration (developing an idea). [112] Meanwhile, Runco and Chand [96] developed a two-tier creativity model. The primary tier has three components: problem finding, ideation (fluency, flexibility, originality), and evaluation. The secondary tier has two components: knowledge, declarative and procedural, and motivation. In addition, two styles of thinking, convergent and divergent, were found to have guided creativity in problem solving, see Runco & Albert. [97] Convergent thinking charts one specific path to reach a single solution to the problem whereas divergent thinking is tentative as it investigates ideas and patterns to arrive at ‘feasible’ answers to the problem. [98] Sternberg statistically examined the inter-correlational associations between creativity, intelligence and wisdom using questionnaires. [108] Three inter-correlation matrices were reported in the findings. Intelligence and wisdom showed very strong correlations (median $r=0.68$) followed by intelligence and creativity (median $r=0.56$) and the least correlation values were reported between wisdom and creativity (median $r=0.42$). [108]

Finke, Ward & Smith [28] studied the role of imagery-based cognition in creativity, and introduced a problem-solving model, which has two phases: generative and exploratory. In the generative phase one constructs mental representations, called pre-inventive structures, to promote creative discovery. The pre-

inventive structures and their properties are then interpreted in the exploratory phase to arrive at desirable solutions and products. Furthermore, Bartlett, cited in Rowe, maintains that external visual stimuli from objects are related to pre-existing structures in the brain, both of which are used to provide useful information for creative problem solving. [95]

In summary, the bulk of research has focused on tests of creativity as a 'process' which uses a battery of measures that examine verbal abilities, visual abilities and unusual uses test. In comparison, research on the creativity of 'products', is less in volume. Amabile [3] attempted to develop a 'consensual' definition of creative product which aimed at establishing a reliability assessment from a group of judges on the creativity of products. Amabile's assessment tool for creative products had three dimensions: creativity judgement, technical judgement and aesthetic judgement. However, both the idea and practice of using appropriate judges to assess a product was pioneered by Mackinnon [60] who examined the traits of personality associated with creativity in architecture by independently asking five professors of architecture in the US to nominate the forty most creative architects in the US. According to Mackinnon, it was important to reach an agreement between the five experts on 'who are the more and who are the less creative workers in a given field of endeavour'. [60] Based on the results from earlier work, Amabile [4] established a component framework to encapsulate and conceptualise creativity. The framework comprised three components: 'domain relevant skills', 'creativity' related skills and 'task motivation'. The latter component, motivational variables in creativity, though important, received little research attention.

To examine the role of analogical thinking on creativity, Bonnardel [12] conducted an experiment with 10 volunteer students in Applied Art from the Technical School of Marseille, France and concluded that analogical reasoning 'as a source of inspiration' is very important for creativity and having cognitive 'constraints' can help the 'emergence' of new ideas.

On architectural creativity, 17 graduating architectural students were rated in terms of creativity by two professors au fait with their work, and the scores were correlated with a battery of creativity tests. [48] Karlins, Schuerhoff & Kaplan found that rated architectural creativity did not correlate with 'measures of academic aptitude' such as class rank and grades but was related to the 'quality of their design projects and their performance on the spatial factor test'. [48] The spatial issue involves two factors: spatial conception and visualisation. [48]

The above research, however, did not examine architectural creativity and computers. Therefore, there is a need to review the literature on the impact of CAD tools on domains of creativity in problem solving. After a thorough literature review, a handful of papers were found that dealt with the influence of CAD on creativity.

The relationship between creativity and CAD was empirically tested, using interviews, protocol analysis, observations, questionnaires and design diaries. [75] The results showed an occurrence of creative behaviour when CAD was used to solve design problems. Novelty as a design behaviour was recorded in the design process in design diaries from two case studies. Furthermore, findings from data analysis associated creativity of design outcomes, i.e. products, with the use of CAD. [75]

One area in architecture that can be impacted by computer-based tools, such decision support systems (DSS), is design decision making where problem solvers can be helped to develop more creative solutions to design problems. DSS, according to Power and Sharda [90] are interactive systems that help people exploit 'computer communications, data, documents, knowledge, and models to solve problems and make

decisions.’ Three major functions of any DSS are listed as: to facilitate, support rather than automate and adapt to the changing requirements of decision making. [90] Such a system was examined experimentally by Elam and Mead using a three-group design, [24] where the issue of creativity enhancing-DSS was investigated and the finding suggests that computers do have some bearing on decision making procedures of their users and DSS systems may shape the creativity of users’ judgements. [24] However, the study also remarked that the software can weaken creativity as well as augment it. Computer-Assisted Creativity (CAC) systems, a phrase by Gabriel et al., can also act like ‘coach systems’, and provide support with executing creative procedures. These can be regarded as the ‘Computer-Assisted Design (CAD) software of creativity.’ [30] Electronic Brainstorming Systems (EBS), a branch of CAC, on the other hand, encompass brainstorming, the most commonly used method to generate creative ideas. [30] EBS manage to counter the main drawbacks of pen and paper ‘brainstorming, namely group pressure, social loafing, and production blocking.’ [30]

Lubart [58] put forward a taxonomy system, based on four categories of human–computer interaction, to stimulate creativity. He suggested computers may accelerate (a) the generation of creative work through better management, (b) interaction and exchange between persons working together on creative schemes, (c) the employment of creativity augmentation techniques, (d) the creative achievement through ‘integrated human–computer cooperation during idea production.’[58]

Boden [11] posed a question: ‘are computers creative, really?’ Boden suggested that such questions are difficult to answer because they are not scientific but rather philosophical. We cannot even address such questions because the answers are controversial, ‘and highly unclear—philosophical questions.’[11] These include the nature of meaning, or intentionality.’ According to Sarsani [100] computers can be moulded to nurture creativity as well. The phases of the creative activity where software is of benefit comprise ‘generating ideas, recording ideas, manipulating ideas, and implementing ideas.’[59] Many styles and modes of reasoning that are deployed manually, with pen and paper, can potentially be captured in a software package. The advantages are the small storage space needed and simplicity of access. [100]

Jennings [45] argues that ‘creative artificial intelligence systems’ are a type of software, which is more than just an extension of the author’s own creativity. Instead, such systems must have what Jennings call ‘creative autonomy’, which happens when a system not only assesses creations by itself, but also modifies its ‘standards without explicit direction’. ‘A system will be said to have creative autonomy if it meets the following three criteria: autonomous evaluation; autonomous change; non-randomness’. [45] López-Ortega [57] maintains that to compute creativity, it is vital to comprehend the cerebral procedures involved, which can be revealed by either investigating people with creative traits or exploring and monitoring brain areas that are stimulate when pursuing creative activities. [57] He also hints that, creativity can be viewed as a ‘meta process’ which synchronises autonomous cognitive processes such as ‘planning or divergent thinking.’ He offers a computer model, written in the Agent Unified Modelling Language (AUML), based on cognitive procedures and their associations, which represents the interaction of cognitive processes surrounding creativity.[57]

The ability of the decision maker and their competence in using creative support system may be an issue that needs to be factored in when relating computer software to creativity levels. In a study with a sample of 215 students with ‘different representational abilities (RAs)’, the effect of deploying 3D-CAD systems on their creative designs was examined by Chang et al. [18] They noted some interesting and important findings. First, students’ RAs correlated positively but ‘moderately’ with their ‘creative performance (CP)’

with 'increased correlation between RAs and the functionality and expressiveness constructs of CP and CP with the iconic representation (IR) construct of RAs'. Second, 3D-CAD markedly advanced students' CP, mostly their 'expressiveness and functionality'. [18] In an experimental two groups design, one cluster working with pencil-and-paper and the other with creativity-boosting software, Marakas and Elam [62] found that the design strategy employed by the subjects, not the medium used, is the one, which correlated with increased level of creativity.

Nake [78], in his review of 'creativity in early computer art' concluded that 'like any other tool, material, or media, computer equipment may play important roles in creative processes'. People's creativity can be boosted, activated, and nurtured in several respects. However, Nake [78] went on to suggest that there is nothing indeed thrilling about such a point 'other than that it is rather new, it is extremely exciting, it opens up huge options, and it may trigger super-surprise'. [78]

Bown [15] took a wide view on creativity suggesting, 'computational creativity' deals with wider domains of creation beyond human creativity to acts of creativity where and when they happen. He calls for adopting a wider view of creativity as the activity of creating original objects, not reduced to a collection of 'psychological capacities'. 'Computational creativity', according to Bown, as a concept must not be modelled just on the mould set by human creativity but rather, we have view creativity as an all-purpose process that can be employed where innovative objects occur. Furthermore, Bown [15] sees a difference between two forms of creativity: 'generative' and 'adaptive' creativity. The former is associated with a process rather than a value of a product whereas in the latter type, which one can call functional, objects are created as 'adaptive responses by a system to its situation.' [15]

Bourgeois-Bougrine et al. [14] argued that comprehending both creativity and development tools has turn into a necessary skill for engineers and a part of their basic educational training. In an experiment study with 27 French postgraduate engineering students This study aimed to appraise the success of development tools with regards to creativity during a 'conceptual product design challenge'. The main findings were: 'creative students applied more creativity tools than the less creative ones'; the character of the creativity tools should match the stages of the creativity route; exceedingly guarded and well-organized approach can obstruct creative accomplishment. [14] The majority of students who applied 'Analogies, Personas, mind mapping, purge, and/or reverse brainstorming' constructed 'unique ideas, a variety of concepts as well as technological innovations.' [14] Candy [16] maintained that the characteristics of any systems, such as materials and tools that mould a section of the creative activity are in themselves critical features that 'influence the way creativity takes place, i.e. the process'. According to this study, the components of creative cognitive style are: 'problem formulation, ideas generation, strategies and methods and the application of expert knowledge'. [16] When combined in a particular way by a particular individual, the result is creative. The traits of the support environments, whether computer-based or not, have to be decided based on our knowledge of creative route. However, if a support environment is intended to sustain the 'creative process' of the creative operator, the question arises as to 'how far does it, in turn, change that process?' [16] Furthermore, this study deduced, to scaffold the demands of the creative user the support system has to enable: knowledge accumulation and assessment is the application of domain knowledge in the generation of innovative out- comes such as scientific results, design objects or apparatuses; visualisation, i.e. operating with visual data such as pictures, sketches, tables, diagrams, flow charts, graphical objects, that are 'specific to the domain'; co-operation between teams on complex design problems. [16] For a better understanding of creativity field studies of creativity of subjects in natural settings, rather than in regulated laboratories should be pursued.

The role of ‘precedents’ in boosting creativity during ‘iterative’ design to solve ‘open ended problems’ in CAD was examined by Doholi and Umbarkar. [21] The main findings from this study confirmed that precedents lessen ‘design variety’ and in turn have a marginal impact on ‘novelty and quality’, both are important dimensions of creativity. Iterative design and ‘group settings’ progress design function but not novelty. Regularly altering the ‘design requirements’ in increments does not amplify novelty. Groups aid design appraisal but can hamper problem structuring and enactment. [21] Liu et al. [55] maintain that current computer-aided creative design systems have numerous inadequacies, so human-based creativity seems to be the most rational method to follow when a designer interacts with a system. The designer still is in the decisive position in terms of decision making regarding the ‘creative thinking such as intuition thinking and inspiration thinking’, and the system offers essential information and valuable gizmos to stimulate the designer’s innovative thinking. [55]

The impact of computation on the creativity of the design process was investigated among engineers where CAD tools were found to have a decisive bearing on enhanced interaction, communication and visualisation by Robertson and Radcliffe’s. [93] A survey of engineers confirmed that the use of CAD was found to push the user to faultlessness in problem solving and the constant use of CAD did not induce negative motivation which could negatively affect creativity. Also ‘premature fixation’, that CAD software can push the engineer to espouse a particular solution, was not an issue among CAD users. [93] Meanwhile, Holt [43] has identified a number of non- commercial CAD tools that are thought to ‘facilitate creative thinking in problem solving activities’ in design. Although his investigation is theoretical in nature it makes some interesting predictions regarding the future development of CAD tools in that any development should focus on creating a computer supported design environment that can provide specialised knowledge-based systems where designers can test their design hypothesis. Gomez et al. [33] highlight two important issues in software design, which are important for creativity: analogy and retrieval. They maintain that ‘analogy is an important reasoning process in creative design’ and to introduce creative analogies, software should facilitate the ‘semantic’ or ‘structural’ retrieval of candidate analogies from knowledge-based systems. Meanwhile, Nakakoji, Yamamoto and Ohira [77] introduced a new type of creativity, called ‘collective creativity’ and developed two computer systems that support ‘designer’s collective creativity by accessing ‘representations ‘generated by other designers in the community’. They also observed the way that designers interacted with both systems and concluded that any system that is intended to support collective creativity has to encompass design knowledge which has a context, is reliable and creates motivation, i.e. make designers love what they are doing. Furthermore, Tennyson and Breuer [111], after an empirical research, conclude that computer based ‘dynamic’ simulation can enhance creative problem-solving techniques. The simulation process they introduced was a three-stage process. In the first instance the simulation provides the user with useful information about the context of the problem. The second stage requires the users to provide their own solution to the problem. In the final stage the simulation evaluates the submitted proposal and offers some feedback.

Finally, Jonson’s recent research findings [47] on the use of different design media, i.e. sketch/ word/ model/ computer) by two small groups of designers have challenged and refuted two long held notions: that conventional sketching is the primary conceptual design tool and that ‘computing is unsuitable for conceptualization.’ [47]

In architecture there were even fewer empirical studies that dealt with the influence of the computer, or CAD tools on creative cognition. A study by Hanna and Barber [37] measured attitudes of architecture students in the studio toward the design process at two points in time: before and after using the computer.

The analysis revealed a significant difference in attitudes toward design variables when subjects were asked to use CAD in design. The results suggest that the use of CAD has yielded a positive influence on the creative process. CAD seems to: facilitate the 3D visualisation and testing of design concepts, increase ideation fluency and help the conception of complex geometry. In summary, figure 6 displays a diagram that helps the reader to quickly capture the essence of this section.

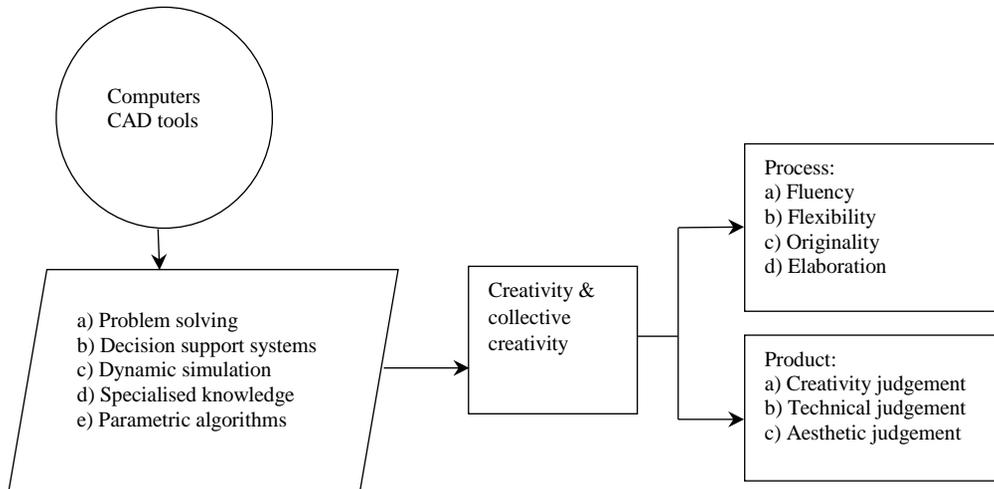


Figure 6: Association between computers and creativity

8 Conclusions

This systematic review paper, which may be the first of its kind in architectural design computation, attempted to synthesize the results from numerous primary theoretical and empirical literature papers to articulate a coherent argument about the relationship between CAD software and the design process, aimed at creating a focused description of a field, namely computer-mediated-creative-cognition. The search results from search engines were analysed statistically to determine the correlation between the search engine and search outcome in terms of research paper hits in terms of title and/or abstract relevance. The discovered papers were evaluated twice based on inclusion criteria. Many questions regarding the outcome from search engines were addressed more adequately using a significance-based statistical tests and procedures. In addition, this methodology and the statistical tests associated with it can be adapted and used for the appraisal of outcome from other research engines in terms of relevant research papers. The odds ratio statistics and the Kruskal-Wallis test with Monte Carlo Simulation are extremely useful measures to evaluate the relative effectiveness of a particular search engine over another in producing relevant papers.

After an exhaustive literature review and analysis, it is obvious that there is a gulf in opinion on whether CAD does help or hinder the creative process or creative decision making in design. There is also some uncertainty on its potential for concept formulation at the early design stage. One of the fundamental problems with the literature in this area is that authors' state of competence in using CAD tools remains ambiguous or undeclared, to say the least. This study argues that having a hands-on knowledge, i.e. the skills and ability to fluently use CAD tools, is of vital importance to the appreciation of their design potential and paramount to the process of making of an objective assessment about their suitability for design. There is also the misguided assumption that educational research in CAD should lead to 'closed' rather than

‘open’ generalisations, which can transcend into a new theory for CAD pedagogy in education. Furthermore, there is little consideration in architectural research regarding CAD on how this research can assist architectural practice in terms of initiating new avenues for the deployment of CAD in architectural practices. In other words, there seems to be no linkage between architectural researches in CAD and architectural practice of CAD.

Furthermore, the study draws some additional conclusions. Firstly, on the design tool relationship, it appears that the computer is more than just a tool; it is a medium and may become a design partner. The thought process that led to this assertion was largely influenced by the philosophical literature on technology. To think about tools in an intellectual manner, we should view them beyond their immediate use in design to their essence as a technological device, which can determine the ‘selective’ act of ‘bringing forth’ chosen by the designer as they favour and ultimately force her/him into a specific way of thinking. This was put very succinctly by Heidegger when he stated, ‘wherever instrumentality reigns, there reigns causality’. Therefore, the idea that the tool is a slave and the designer is a master, which persisted for so long in design studios in architecture, lacks validity and the truth behind it needs to be questioned and challenged.

Secondly, on the impact of the computer on creativity there is some evidence to suggest it can help creativity in areas of visualisation and communication, ideation fluency and solving problems regarding the complexity of designed objects, but it may be not so helpful for conceptual design at the early stage. However, most research that explored the influence of CAD on creativity took place at a time when CAD software was largely viewed as a drafting rather than a design tool and where there was very little knowledge on parametric tools and their deployment in design, in both education and practice. It is anticipated that creativity in design will be enhanced when designers become more aware of the generative nature of parametric tools, particularly the algorithmic editors such as Grasshopper, and when the use of these tools pervades more and dominates in both architectural practice and education. Other than that the use of algorithmic editors in design is rather a new phenomenon, it is extremely exciting as an event since it opens up huge design options, and it may spark off high-quality revelation in problem solving.

The implications from this review paper for design studios in architectural education can be summarised as follows. Tools students use in design will influence their design outcome and in turn their architectural style. The use of paper-and-pencil will produce a type of building forms that will be different from those generated by the extensive use of CAD in the design process. Also, if a student has a limitation in using a particular tool then this will have a negative impact on their ability to design creatively. As for software developers, they should consult and head lessons from the rich literature on creativity, its domains and measures and program software packages which can focus on ideation rather than drafting. If ideation fluency and variety become central to software development, this will also make CAD tools more useable at the conceptual design stage, more fun to work with and easier to interact with. An emphasis should also be placed on developing specialised CAD tools and knowledge-based systems that can target specific design issues during problem solving. In summary it maybe that tools are not passive devices, perhaps they can force the designer to think in a particular way and as a result create a particular type of form. This area requires further investigation. Also, computer-enhanced creativity in design maybe possible, but the process employed by the users and their competence in using the tool are also important factors in developing a creative product.

In closing, the influence of design tools on the nature of design outcome has pervaded other design and

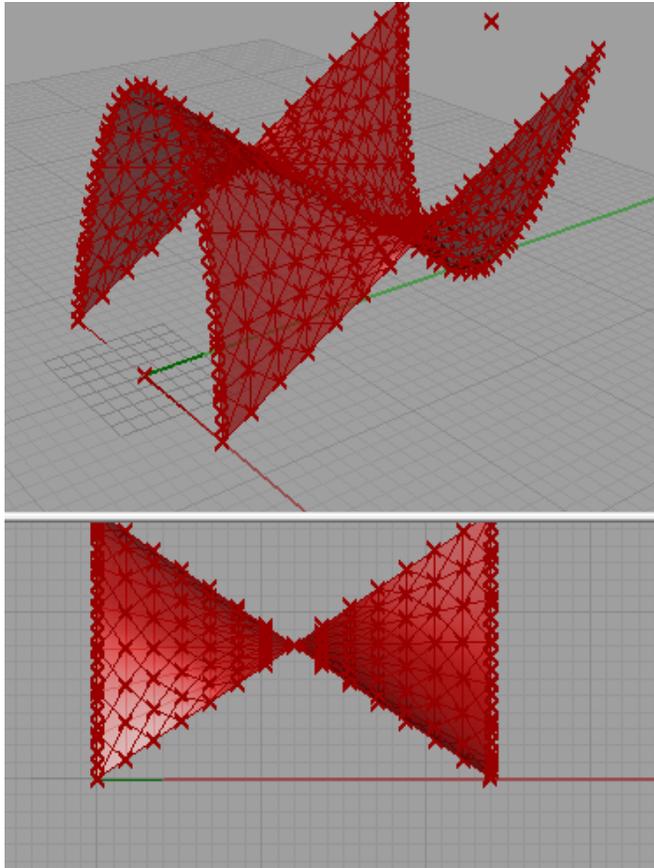
engineering disciplines. In Formula one Newey, Red Bull's chief technical designer, puts it eloquently: 'I'll often start with a sketch on a piece of A4. Then I'll develop that on the board, using freehand sketching.' [68] Contrasting this is Steele's idea of allowing the computer to lead and 'guide the process'. [107] citing examples such as Frazer's 'evolutionary paradigm of evolving concepts by mutating computer models in a simulated environment' and Karl Chu's 'genetic space' at X KAVYA and the lesser extreme work of Lars Spuyboek at NOX. [107]

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Appendix 2: A doubly ruled surface from the generative algorithm in appendix 1.



International Journal of Design Sciences and Technology

Design Sciences, Advanced Technologies and Design Innovations

Towards a better, stronger and sustainable built environment

Aims and scope

Today's design strongly seeks ways to change itself into a more competitive and innovative discipline taking advantage of the emerging advanced technologies as well as evolution of design research disciplines with their profound effects on emerging design theories, methods and techniques. A number of reform programmes have been initiated by national governments, research institutes, universities and design practices. Although the objectives of different reform programmes show many more differences than commonalities, they all agree that the adoption of advanced information, communication and knowledge technologies is a key enabler for achieving the long-term objectives of these programmes and thus providing the basis for a better, stronger and sustainable future for all design disciplines. The term sustainability - in its environmental usage - refers to the conservation of the natural environment and resources for future generations. The application of sustainability refers to approaches such as Green Design, Sustainable Architecture etc. The concept of sustainability in design has evolved over many years. In the early years, the focus was mainly on how to deal with the issue of increasingly scarce resources and on how to reduce the design impact on the natural environment. It is now recognized that "sustainable" or "green" approaches should take into account the so-called triple bottom line of economic viability, social responsibility and environmental impact. In other words: the sustainable solutions need to be socially equitable, economically viable and environmentally sound.

IJDST promotes the advancement of information and communication technology and effective application of advanced technologies for all design disciplines related to the built environment including but not limited to architecture, building design, civil engineering, urban planning and industrial design. Based on these objectives the journal challenges design researchers and design professionals from all over the world to submit papers on how the application of advanced technologies (theories, methods, experiments and techniques) can address the long-term ambitions of the design disciplines in order to enhance its competitive qualities and to provide solutions for the increasing demand from society for more sustainable design products. In addition, IJDST challenges authors to submit research papers on the subject of green design. In this context "green design" is regarded as the application of sustainability in design by means of the advanced technologies (theories, methods, experiments and techniques), which focuses on the research, education and practice of design which is capable of using resources efficiently and effectively. The main objective of this approach is to develop new products and services for corporations and their clients in order to reduce their energy consumption.

The main goal of the *International Journal of Design Sciences and Technology* (IJDST) is to disseminate design knowledge. The design of new products drives to solve problems that their solutions are still partial, and their tools and methods are rudimentary. Design is applied in extremely various fields and implies numerous agents during the entire process of elaboration and realisation. The International Journal of Design Sciences and Technology is a multidisciplinary forum dealing with all facets and fields of design. It endeavours to provide a framework with which to support debates on different social, economic, political, historical, pedagogical, philosophical, scientific and technological issues surrounding design and their implications for both professional and educational design environments. The focus is on both general as well as specific design issues, at the level of design ideas, experiments and applications. Besides examining the concepts and the questions raised by academic and professional communities, IJDST also addresses the concerns and approaches of different academic, industrial and professional design disciplines. IJDST seeks to follow the growth of the universe of design theories, methods and techniques in order to observe, to interpret and to contribute to design's dynamic and expanding sciences and technology. IJDST will examine

design in its broadest context. Papers are expected to clearly address design research, applications and methods. Conclusions need to be sufficiently supported by both evidence from existing research (reference to existing design research knowledge) as well as strong case-studies from any design discipline. A paper must contain at least one chapter on research questions, methodology of research and methods of analysis (the minimum length is 1500 words). The concluding chapter (the minimum length is 1000 words) will summarise the paper and its results. The concluding chapter also examines and discuss applications, advantage, shortcomings and implications of the investigation for both professional and educational design communities as well as for the people and the society. Also, authors are also encouraged to include in this chapter a discussion of the possible future research that is required or is possible in order to enhance the research findings.

The papers considered for IJDST cover a wide range of research areas including but not limited to the following topics: Design research, design science, design thinking, design knowledge, design history, design taxonomy, design technology, design praxeology, design modelling, design metrology, design axiology, design philosophy, design epistemology, design pedagogy, design management, design policy, design politics, design sociology, design economics, design aesthetics, design semantics, design decision-making, design decisions, design evaluation, design sustainability, design logic, design ontology, design logistics, design syntaxis, design ethics, design objective, design responsibility, design environment, design awareness, design informatics, design organization, design communication, design intelligence, design evaluation, design education, design theories, design techniques, design methods, design operations, design processes, design products, design users, design participation, design innovation, design inspired by nature, design case studies, design experiments, etc.

The *International Journal of Design Sciences and Technology* is devoted to further exploration of all themes and issues that are directly or indirectly relevant to the exploration, introduction, discussion of design sciences and technology, cross referencing domains and any other themes emerging in the future.

Instructions for Authors and Review Process

Pre-review Stage (Editor Global Review): Papers can only be considered for review when they deal with a subject relevant to the content of the journal. In addition, all papers submitted must follow the journal's paper structure and author instructions before they can be considered for review. These instructions also affect the content of the paper. The preferred size of a paper is about 10000 words (The minimum length of a paper is about 7000 words). The title must not be longer than seven words. Subtitles are not permitted. The maximum length of the abstract is 150 words. The paper must contain an introductory chapter with extensive literature review of similar research (the minimum length of the introduction chapter is about 1000 words). The paper devotes at least one chapter to detailed discussion of research questions, research analysis and research contributions (the minimum length of this chapter is about 1000 words). The conclusion will summarise the research and its results. In addition, this chapter includes a detailed discussion of applications, advantage, shortcomings and implications of the investigation as well as future research for both design professionals and the design education (the minimum length of conclusions is about 1000 words). Submit a paper at this stage as PDF.

Review Stage (Peer Review): Only papers meeting all IJDST requirements can be considered for review. All papers are reviewed by at least two expert reviewers. The main author of a reviewed and accepted paper will be notified with instructions to resubmit the paper. All reviewed and accepted papers have to be resubmitted, implementing reviewers and editors' comments and/or suggestions. Only accepted papers conforming to instructions will be considered for publication in the *International Journal of Design Sciences and Technology*. A paper should follow the IJDST paper structure. The review process will be repeated until all requirements are met.

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- [3] **Buxton, W** (1997) *Living in Augmented Reality: Ubiquitous Media and Reflective Environments*. In: Finne K, Sellen A and Wilber S eds, *Video Mediated Communication*, Erlbaum, Hillsdale NJ, 363-384
- [4] **Dixon, NM** (2000) *Common Knowledge: How companies thrive by sharing what they know*, Harvard Business School Press, Boston, MA

- [5] **Djenidi H, Ramdane-Cherif A, Tadj C and Levy N** (2004). Generic Pipelined Multi-Agents Architecture for Multimedia Multimodal Software Environment, *Journal of Object Technology*, 3:8, 147-169
- [6] **Gorard, S and Selwynn, N** (1999) Switching on to the learning society? Questioning the role of technology in widening participation in lifelong learning, *Journal of Education Policy*, 14:5, 523-534
- [7] **World Bank** (2002) Social assessment as a method for social analysis, World Bank Group [www.worldbank.org/gender/resources/assessment/samethod.htm]

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