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Architects' Perceptions about Sustainable Design Practice and the Support Provided for This by Digital Tools: A Study in Australia

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Abstract: The fundamental goal of sustainable design for the built environment is to optimise the performance of buildings to minimise their impact on the environment. To achieve this goal, contemporary architects use a range of digital design environments, such as Computer-aided Design (CAD) or Building Information Modelling (BIM) tools. These allow architects to implement sustainable design principles and make optimal decisions about the ecological and energy properties of the building or environment being designed. Past research about architects' uses of these tools for sustainable design have been focused on their capacity for optimising building performance and meeting architects' design needs. In parallel, other studies have identified technological barriers and readiness factors for implementing sustainable design in several countries, including Australia. Researchers have suggested that presently, most architects are unlikely to perceive Building Performance Analysis (BPA) as their responsibility. It has also been found that the digital design tools need to more effectively support sustainable design. However, despite this body of past research, to date there is a lack of a more holistic understanding regarding architects' perceptions about the alignment between sustainability practices and the capacity of digital design environments for supporting these, particularly in Australia. This paper addresses this knowledge gap, by presenting findings derived from semi-structured interviews with 18 professional architects in Australia, each with experiences in sustainable design and the use of digital design tools. The results are used to establish a conceptual model, which illustrates the relationships between a variety of factors affecting architects' sustainable design practices. The findings suggest that in Australia, architects have more negative than positive experiences regarding their sustainable design practices, due to factors ranging from those related to the practice itself, to the digital design technologies and budget available for supporting their goals. This study also identifies an urgent need to enhance and better align the capabilities of digital design technologies with sustainable outcomes and associated organisational objectives, which the new model can assist in understanding and facilitating.

Keywords: sustainable design practice; architects' perceptions; digital design environments

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1. Introduction

Construction and building operations within the Architecture, Engineering and Construction (AEC) industry account for significant energy consumption [1], producing up to 39% of energy-related CO_2 emissions [2]. Such emissions have a significant negative impact on the environment, by worsening the greenhouse effect and accelerating climate change. Research has shown that applying sustainable design strategies can effectively reduce building energy consumption by up to 80% [3], and sustainable design practices are becoming vitally important across the AEC sector globally including in Australia. The United Nation's Sustainable Development Goals (SDGs) also emphasise the critical importance of architects and designers designing more ecologically advanced environments.

One standard definition of sustainability is "to meet the needs of the present without compromising the ability of future generations to meet their own needs" [4]. Sustainability significantly affects society, the environment, and the economy in various ways. The AEC industry represents one of the largest areas of economic activity, and via sustainable design it is capable of significantly reducing building energy consumption. The ultimate intention of sustainable design is to "eliminate negative environmental impact completely through skillful, sensitive design" [5], and designers seeking a more sustainable solution often rely on digital technologies for developing more efficient and responsible buildings to meet both environmental and economic demands. In fact, digital practices have become an innovative force throughout the life cycle of contemporary AEC projects.

The digital technologies used to support AEC professionals to design in more sustainable ways are often embedded into the primary software platforms used across the sector, such as Computer-aided Design (CAD) and Building Information Modelling (BIM) systems. Although digital technologies are important for modelling environmental and socio-economic issues during sustainable building design [6], current digital technologies can still be ineffective in supporting sustainable design processes [7]. For example, research suggests that most sustainable design tools have a range of limitations, such as not being able to conduct comprehensive life cycle assessment [8], lacking user-friendly interfaces, requiring more seamless integration with CAD software, being unsuitable for conceptual design phases, requiring excessive data-input for initiation, and lacking an extensive building component library for complex design and evaluation [9]. Such potential problems, associated with the use of digital technologies in sustainable design, may result in architects making poor decisions during the design process, ultimately leading to suboptimal performance of the buildings and environments being created.

Therefore, it is critical to understand architects' current sustainable design practices, especially the challenges and obstacles that may arise during the processes they use to create more sustainable outcomes. It is also important to align such understandings with the capabilities and readiness of digital technologies to better support these practices. Such a holistic understanding of the topic will assist architects and architectural firms and organisations to better implement and refine their sustainable design practices, and provide software developers with new insights about the needs of the sector for more optimal development of sustainable design tools. Focusing on the Australian context, this paper aims to explore architects' perceptions of their own sustainable design practices and the effectiveness of digital design environments for supporting these practices. The next section, Section 2, describes the background of the research to provide an understanding of the latest literature on this topic. Section 3 describes the research method including a description of the semi-structured interview approach used and the main themes for analysis. Section 4 presents the interview results, and finally Section 5 concludes the study with a summary of the results and implications of this study.

2. Background

2.1. Sustainable Design Practices in Australia

Sustainable design for the built environment can reduce the ecological footprint of buildings, providing long term economic, environmental and social benefits. Almost half of the fossil fuel produced each year in the world is consumed by buildings and their occupants [10]. In some parts of the world, sustainability is a largely theoretical phenomenon [11], and the practice of "greenwashing" can also sometimes mislead design industries [12]. However, in many other countries, for example, Australia, an "Environmentally Sustainable Australia" is listed as the first national research priority, and there are drives to improve the performance of both buildings and urban environments, especially considering the continuing increase of urban density. There is, however, considerable complexity involved in optimising the sustainable or ecologically sound aspects of a building design. Factors such as the building materials, openings, shading, orientation of the building etc., can all impact the building's performance. These factors can be further extended to other influences such as site sustainability, the usage and efficiency of energy, water, waste and other resources [13]. These factors need to be considered collectively, balancing with other aspects of architectural design such as functionality, building appearance, and budget. Furthermore, such considerations often conflict with one another, resulting in challenges for architects who are seeking to produce more sustainable buildings. In this context, digital design tools can play a particularly important role to assist architects in dealing with such complexity and tackling challenges and conflicts by quantitatively analysing and optimising design solutions through computation.

Watson [14] asserted that there is an ethical obligation for architects to contribute to the preservation of the Earth's resources through design. In practice, however, meeting all sustainability requirements in the design process can be challenging for architects [15]. Sustainable design practices are multifaceted, requiring architects to master both innovative technology-driven and traditional vernacular solutions [16]. Research has also identified that sustainability needs to be taken into consideration from the early conceptual design stage to achieve optimal impact [17–19], as it can minimise potential changes to the building during later project stages which typically result in higher construction costs [20].

Current research has investigated architects' sustainable design practices from several perspectives. For example, Martek et al. [21] discussed the barriers to sustainable design in Australia, including limited user awareness, the lack of end-user demand, challenges of socio-spatial embedding and industry complacency. By interviewing design experts, Naboni [8] concluded that architectural firms seem to have appropriate design strategies and digital tools to facilitate sustainable design in general, representing a certain level of technological readiness. Soebarto et al. [22] conducted a major survey in Australia, India, the US and the UK, to specifically investigate how architects conduct Building Performance Analysis (BPA) simulation, a critical approach to sustainable design. Their results suggest that amongst other issues, most architects do not perceive BPA to be their responsibility, which has prevented the effective usage of BPA simulation tools in practice. Focusing on the Australian context, Yu and Ostwald [7] conducted a more recent survey evaluating the usefulness of current digital tools for supporting sustainable design, and their preliminary results suggest that digital design tools are in need of further development and improvement from multiple perspectives.

2.2. Digital Design Environments in Supporting Sustainable Design

The ongoing digital innovation process across the AEC sector has posed challenges to architectural practices [23]. Cory and Bozell [24] suggested that the advancement of digital technologies has been generally beneficial for AEC professions; however, it has also carried associated concerns relating to the additional investment required in terms of both costs and time, and users' software learning curves, as well as the ability of software to address different design and modelling needs, and to effectively support users in design, collaboration, communication and maintenance.

BIM, as one of the most widely adopted technology platforms in the AEC sector, can assist AEC professionals with planning, design, construction and facility management for a building project [25], and support sustainable design [26]. Past research suggests that adopting digital technologies such as BIM in the sustainable design process can assist architects to achieve optimal solutions, through various BIM-enabled features such as simulations which predict the energy performance of a building design [27,28].

Two additional digital design tools used in architectural practices to support sustainable design are BPA simulation (either standalone or integrated into other primary architectural design software), and parametric simulation. Some examples of standalone BPA simulation tools are *EnergyPlus*, *Sefaira*, and *Ecotect*. Primary architectural design software such as BIM platforms, including *Autodesk Revit* and *ArchiCAD*, contain integrated BPA or other simulation capabilities, for example, *Green Building Studio*. Performing BPA early in the design process is beneficial for identifying and adopting sustainable design strategies in building projects, for example, in achieving energy-savings [29].

Parametric simulation tools are being increasingly applied to support sustainable design processes. Parametric design is a rule-based design process, where multiple design solutions can be developed in parallel [30]. The benefit of applying parametric design is that it can support parallel and iterative design analysis and optimisation. What is significant, and rarely mentioned in most literature, is the degree to which parametric design environments can shape the way that architects think and operate [31]. Parametric simulation tools that can be utilised to support sustainable design include *Digital Project*, *Rhino* and *Grasshopper* (notably, some *Grasshopper* add-ons such as *Honeybee* and *Ladybug* are specifically for sustainable design). Parametric design, by applying algorithms and parameters, can effectively address environmental concerns in architectural design considerations, in terms of space, form and structure, therefore providing improved opportunities for integrating sustainable design into the design process [32–34].

In the design literature, the impact of digital technologies has often been considered on design in general, but not specifically on sustainable design. A number of more recent studies of architects' sustainable design practices have attempted to address this gap, but focused solely on the roles of different digital technologies [7,8] in supporting sustainable design such as in BPA [22]. Despite this, there remains a lack of research emphasis on the architects themselves, for example, to explore more holistically their perceptions, and their experiences with different digital design environments that support their sustainable design practices. There is also an urgent need to consider and adjust the alignment between current digital design capacities and architects' sustainable design aspirations, to achieve more optimal outcomes. Therefore, this study aims to explore the perceptions of Australian architects about their sustainable design practices and the usage of digital environments that support these. The main research questions being explored are: (1) What are the important factors affecting architects' sustainable design practices, and what are the relationships between those factors? (2) How do digital design environments support architects' sustainable design practices, and what are their current challenges and future roles?

3. Research Method

3.1. Semi-Structured Interview

To address the knowledge gap identified in the previous section, and answer the two research questions, this research surveyed experienced professional architects in Australia, utilising a semi-structured interview method. The interview method is considered suitable for detailed studies exploring the perceptions of participants, allowing in-depth investigations on a particular topic with a relatively small sample size. Semi-structured interviews in particular, have a fixed set of start-up or 'trigger' questions, but the interviewer can flexibly add questions based on the interviewee's individual answers as they emerge during the process. Semi-structured interviews are a common qualitative research method, which provide the capacity to ensure that key questions closely related to the research aim are asked, and also enable a certain degree of flexibility to obtain more comprehensive results [35]. Compared with other qualitative methods, the semi-structured interview format maintains sufficient focus on relevancy to the research topics, while still being responsive to individual interviewees [36].

In this study, 18 professional architects in Australia were recruited to participate in the interview. All recruited architects had more than five years of professional working experience in the industry. Potential participants were initially selected based on their public profile from their company web site and/or from LinkedIn. After subsequent screening based on their career experience and duration, and the projects they have worked on, approximately 50 architects were invited by email to participate. Ultimately, 18 professional architects responded and participated in the interviews. The 18 participants' design experiences covered a wide range of project types including residential, commercial, healthcare and interiors, amongst others. The interviews were conducted via Zoom throughout 2020, in accordance with the social distancing restrictions at that time. Each interview session took around 30 min, and the conversations were recorded for subsequent analysis. Human

Research Ethics approval to conduct this study was awarded following an extensive review and refinement process for the method.

Table 1 shows the initial interview questions which were focused on three key aspects: the architects' sustainable design practices, digital design environments in use, and their support for the architects' sustainable design practices.

Table 1. Initial interview questions.

		Background Questions
	1	How many years of professional architectural experience do you have?
	2	What types of buildings are your main focus?
	3	Where are you currently working, and where have you worked previously?
		Main Questions
Sustainable design practice	1	What do you feel is the extent, of the application of sustainable design principles in current architectural design practice?
	2	Is sustainable design currently considered at every scale in your practice, in the projects that your workplace undertakes? If not, then what obstacles are currently preventing it? In your experience do clients care about sustainability?
	3	What do you think about the possible future directions of architectural design for sustainability? What do you think may be the future directions for sustainable design in general?
	4	How could sustainable design principles be more widely applied?
Digital tools	5	What are the main digital tools you are using in your practice?
	6	What do you think of current digital tools, in terms of their capacity to support or challenge design thinking and creativity?
Digital tools in supporting sustainable design	7	What do you think of current digital tools, in terms of their ability to support sustainable design? What do you think are the biggest challenges currently in this area?
	8	Do you predict that digital design tools will play an increasingly large part in the future of sustainable design? Do you think that advancements in the areas such as Artificial Intelligence (AI), may eventually change the role of architects?
	9	Do you think that digital design tools will play a more or less important role in promoting sustainable design?

3.2. Main Themes for Encoding Data

The recorded interviews were transcribed and then coded using *Nvivo* software. Multiple codes were allowed for the same segments of interview to capture the content as thoroughly as possible. The main themes for encoding the interview content were developed based on Yu et al.'s [30] computational design model (Figure 1). This recent computational design model effectively encapsulates the complex relationships between the design environment (D_{Env}), design technology (D_{Tec}), design cognition (D_{Cog}) and design creativity (D_{Create}), and provides a closely relevant theoretical foundation for contextualising this study and to guide the analysis. D_{Env} is "the set of conditions that affect a designer's way of working, including relevant computational operating systems and processes"; D_{Cog} is "the set of mental behaviors and operations that occur during the design process". D_{Tec} is "the set of tools which enable the modelling, visualization, analysis and generation of design components". External drivers for design technology (E_{Tec}) include "advances in computer software, hardware and interfaces". External design cognition (E_{Cog}) factors may "include education, enculturation and professional or industry related factors" [30] (pp. 198–199).

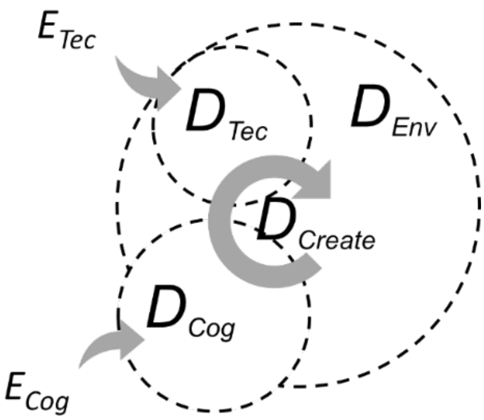

Figure 1. A cognitive model of computational design [30].

While referring to computational or digital design tools, there are clear overlaps between the definitions of the 'design technology or tool' and the 'design environment' and they are often used interchangeably. This model distinguishes the two where D_{Env} encompasses both the technology (D_{Tec}) that supports and enables the design process, and the cognitive operations and behaviours (D_{Cog}) that occur in the process, where D_{Create} also emerges [30].

In addition to the factors illustrated in the computational design model, there are also other factors that can affect architects in their design practices. These include external factors such as those related to the client, budget, regulation, etc., and internal factors such as the architect's digital skill sets and specific design domain knowledge, digital technologies, etc. Figure 2 shows a design practice model adapted from the computational design model described above. Both external factors and internal factors have an impact on design practice, which is beyond the design thinking of designers within the provided design environment. In Figure 2, E_{Deg} represents the external factors affecting the practice, while I_{Deg} represents the internal factors. D_{Tec} is a part of $E_{Deg,}$ which intersects with D_{Env}, while I_{Deg} is separated from D_{Cog} but is a necessary component comprising D_{Env}.

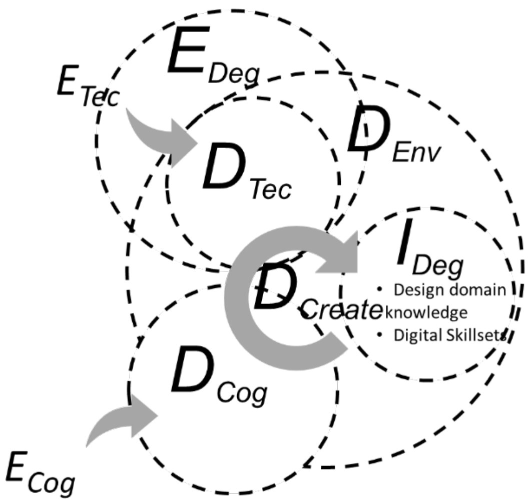

Figure 2. A design practice model of computational design, adapted from [30].

By applying the design practice model (Figures 1 and 2), the following three overarching themes have been identified for categorising the factors that affect sustainable design practices. Table 2 lists the detailed breakdown of factors under the three main themes as *external*, *internal*, and *design cognition* related. The *external* factors that can affect sustainable design practices include the budget, client, design technology, and the nature of the practice. The *internal* factors refer to those related to the architects' experiences, practices or perspectives, such as their skillsets, and the sustainable principles they have adopted. Overlapping with both the *external* and *internal* factors, the *design cognition* related factors include digital technologies as design environments that support or utilise design thinking specifically for achieving sustainable design solutions; they are related to building performance analysis, data-driven design and rule algorithm, design decision making, design problem solving, providing options and design alternatives, streamlining processes, visualisation/simulation, and supporting design thinking and creativity.

Table 2. Detailed breakdown of factors affecting sustainable design practices.

Main Themes	Detailed Breakdown of Factors
Internal	Digital skillsets; Sustainable design principles
External	Budget; Client's brief; Digital design technologies; Nature of practice; Regulation
Design cognition	Building performance analysis; Data-driven design and rule algorithm; Decision making; Problem solving; Providing options; Streamlining process; Visualisation/simulation; Supporting design thinking and creativity

Four perspectives—negative, positive, current and future—were proposed for categorising the architects' perceptions about their sustainable design practices in this study (Figure 3). These four categories complement the three main themes identified above, by providing further understandings about architects' negative/positive experiences of the factors under each theme; and identifying the architects' perceptions about their current sustainable design practices, associated challenges, and future opportunities. *Negative* and *positive* experiences were encoded according to the participants' overall views about their sustainable design practices and the applications of digital technologies for supporting the practices. *Current* refers to interview content related to the participants' current sustainable design practices. *Future* refers to interview content related to the participants' opinions and expectations about various planned or anticipated opportunities regarding sustainable design and supporting technologies.

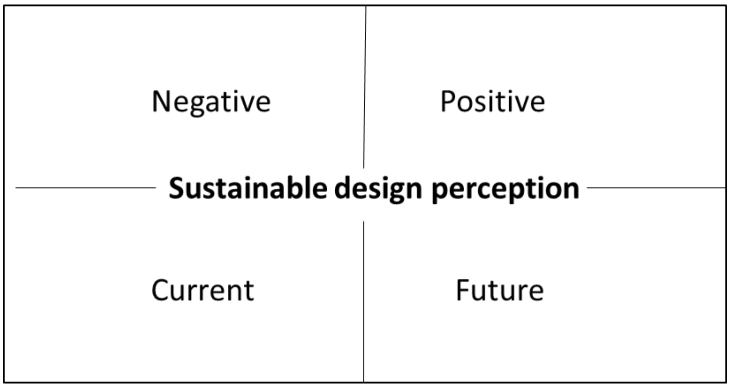

Figure 3. Four perspectives for categorising architects' perceptions of sustainable design practices.

These four categories together with the three above themes are used for encoding the interview data collected to produce the following results.

4. Results

4.1. Overall Distribution of Factors Affecting the Architects' Sustainable Design Practices

This section describes the distribution of factors associated with the three main themes that can affect the architects' sustainable design practices. The overall distribution (%) of factors is presented in Figure 4. The data confirms that the architects discussed the *external* factors (60.62%) most, then *internal* factors (24.07%) and finally the *design cognition* related factors (15.30%). This reflects the impact of external factors such as technologies, regulations, budgets and the client, which are to a large extent outside the architects' control, raising more concerns during their sustainable design practices.

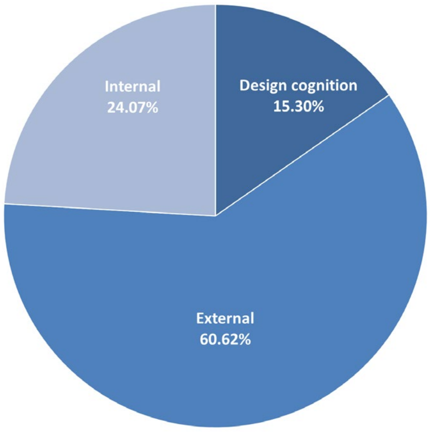

Figure 4. Coding percentages showing the overall distribution of factors in terms of the three main themes.

The detailed breakdown for the coding percentages for the three main themes is shown in Figure 5. The results show that 'digital design technology' has the largest coding percentage (38.19%), followed by 'sustainable design principles' (20.51%), 'regulation' (7.58%), 'budget' (5.50%) and 'client's brief' (4.90%), which mostly represent *external* factors. The least considered factors are related to how digital design environments support the architect, namely in 'providing options' (0.45%), 'problem solving' (0.74%) and 'decision making' (0.59%). From this result it can be inferred that while digital design technologies are potentially dominant factors affecting architects' sustainable design practices, they are not adequately utilised for supporting the architect's specific design processes. This finding could also, however, reflect the nature of the interview questions, which tended to emphasise perceptions about digital design technologies in a more general way. Among the other external factors, 'regulation' represents a relatively large percentage, since BPA (such as energy reports), are often legislated requirements. As one participant put it "*buildings (need to) comply with state legislation around building performance*". The remaining factors such as 'nature of the practice', 'client's brief', and 'budget', all have a noticeable impact on sustainable design practices. Among the *internal* factors, 'sustainable design principles' is the most dominant (20.51%) during the architect's design practice.

The 'digital skillsets' of the architects were also a significant factor. Some architects reported difficulty in using building performance related software, and others highlighted the benefits of hand sketching versus digital tools. However, the majority of the interviewees did not believe these concerns would have negatively affected their design solutions. Within the *design cognition* theme, 'building performance analysis', 'supporting design thinking and creativity', and 'data-driven design and rule algorithm', are the most discussed factors by the participants, and accounted for 4.16%, 3.71% and 2.82% respectively. These three factors are the main areas where the architects perceive that digital tools can play a major role in their sustainable design practices. With parametric tools being increasingly used for sustainable design, both design creativity or innovation and evidence-based design that are key to sustainable design practices, have benefited from these recent developments. As the participants stated: "*So we're using quite a lot of … that helps us pull on some global data to actually understand how our designs respond to contexts*"; " *… programs where tools like Grasshopper have been utilised, to maximise the efficiency or the performance of some chain, for example. And those tools are certainly really valuable*".

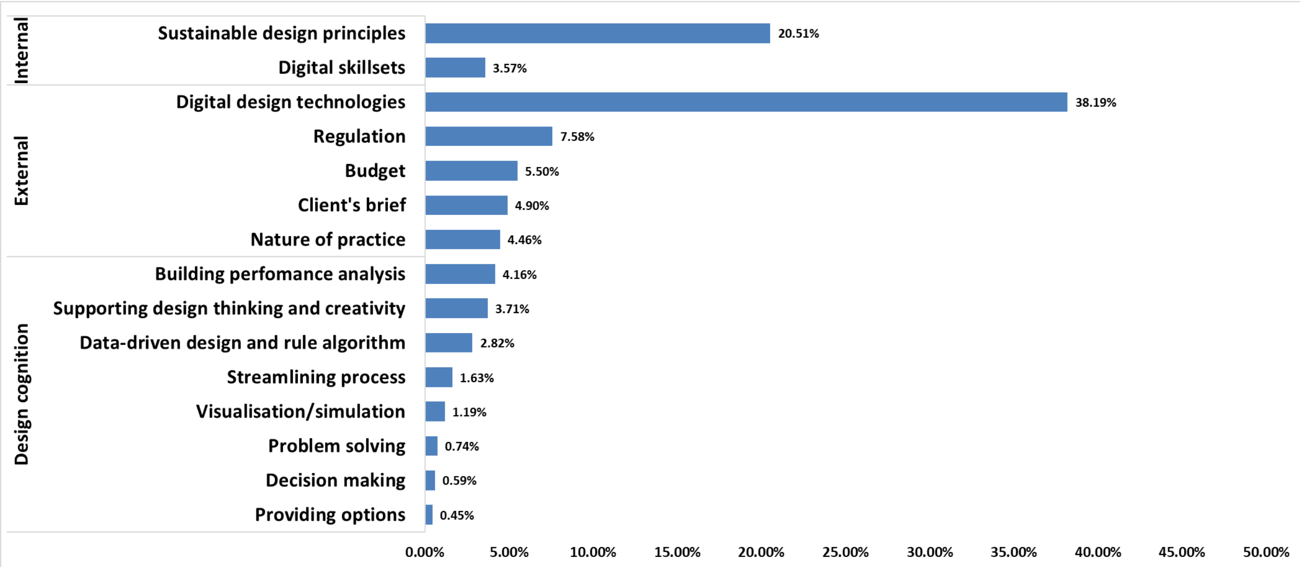

Figure 5. Coding percentages showing the detailed breakdown of factors in the three main themes.

The word cloud generated from the transcribed interview data of all 18 participants is shown in Figure 6. From this figure we can see that the most frequently mentioned term during the interview was 'thinking', followed by 'design', which surpassed the word 'tools'. This finding is potentially indicative of factors related to or supporting design thinking being the most dominant ones when considering sustainable design, more so than the digital tools themselves. As some participants stated: "*You can't get a computer yet to generate what a human experience is like*"; "*I think there's always a source of inspiration in the human mind that can't be achieved through a software program*". In summary, despite 'supporting design thinking and creativity' not being the most dominant factor in terms of coding percentages in the analysis above, from the participants' transcripts, 'design thinking' is nevertheless one of the most frequently used terms when discussing an architect's sustainable design practice, which is in alignment with previous research about the role of computational tools in design: designers thinking/creativity and their knowledge of design is critical during a design process; and while computational tools have an impact on designing, they do not replace design thinking [30].

Figure 6. Word cloud generated from the interview data.

4.2. Architects' Perceptions of Sustainable Design Practices in Relation to Individual Themes

This section illustrates the architects' perception of sustainable design practices in relation to the three individual themes. Figure 7 illustrates their negative and positive experiences about the *internal*, *external* and *design cognition* related factors in the sustainable design practice. The results suggest that across the three main themes, there are more negative experiences than positive ones. The percentage of negative experiences regarding *external* factors is the highest (37.16%), followed by *internal* (11.48%), and lastly *design cognition* related (12.57%). When examining the ratios of the negative versus the positive, internal factors have the highest ratio (11.48%/6.01% = 1.91), which suggests that architects have far more negative experiences than positive experiences about various internal factors such as the development of new skillsets and the implementation of sustainable principles.

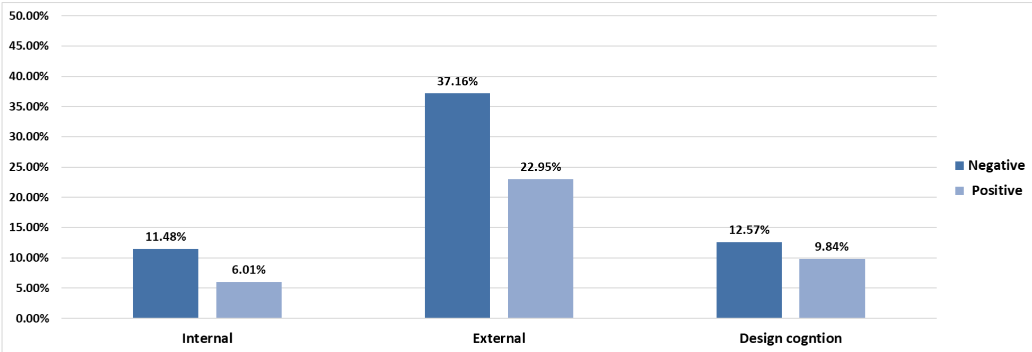

Figure 7. Architects' negative and positive experiences regarding *internal*, *external* and *design cognition* related factors.

The negative and positive experiences of the architects in relation to a detailed breakdown of *external* factors are illustrated in Figure 8. Results show that participants have more negative experiences in all the factors, except for 'client's brief'. Among other external factors, 'budget' has the highest negative versus positive ratio (10.08%/1.68% = 6). This suggests the budget is a major constraint affecting architects' sustainable design aspirations, as one participant stated: "*When it comes to . . . making [sustainable design] work on the day-to-day basis, it's very different, especially convincing clients of the importance and spending their money on it . . . it comes down to money at the end, it's all down to cost and that's the main issue*".

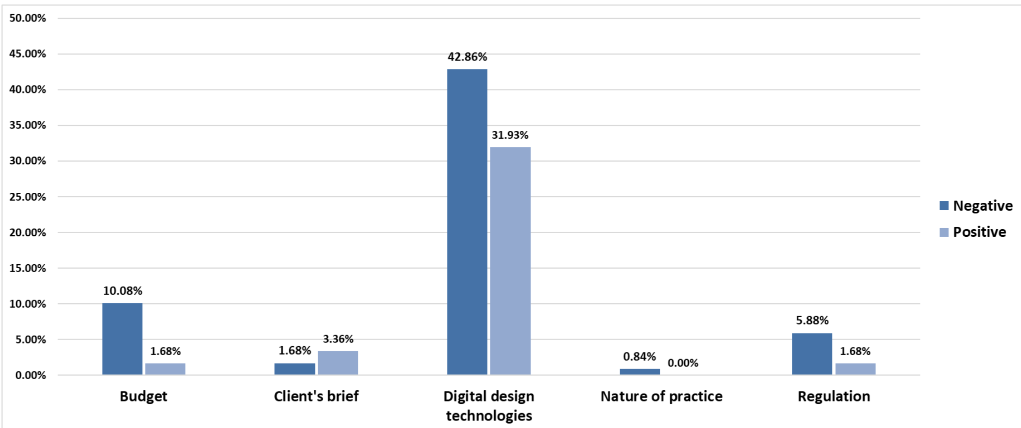

Figure 8. Architects' negative and positive experiences in relation to the external factors.

The negative and positive experiences in relation to individual *internal* factors are shown in Figure 9. The results confirm that for the architects the *internal* factors have more associated negative experiences than positive ones. The negative to positive ratio of 'digital skillsets' is significantly higher (24.24%/6.06% = 4) than sustainable design principles

(42.42%/27.27% = 1.56), which is indicative of the architects' skillsets being insufficient to support sustainable design. Architect participants discussed the effort and time involved in their continuing training, such as always needing to learn and relearn software, while others expressed concern about feeling too old to start learning new software; as one participant mentioned: "*I don't know whether there's a tool that could come into my skillset that I could use that I didn't need to do huge amounts of training*". They also believed that upskilling would not always add a lot of value, because it is often challenging for architects to have both the access to, and the capability of using, new software.

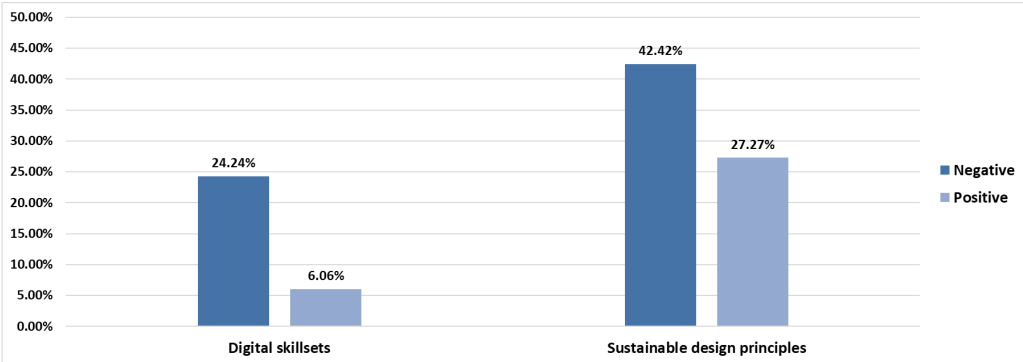

Figure 9. Architects' negative and positive experiences in relation to the internal factors.

The negative and positive experiences of participants in relation to individual factors regarding *design cognition*, can be seen in Figure 10. Interestingly, the results show that there are more positive than negative experiences, about 'building performance analysis' and 'providing options'. That suggests architects are relatively satisfied with the current digital design environments for supporting building performance analysis, and the environments' ability to provide options and design alternatives (especially with parametric design). As one participant stated: "*Using a sustainability tool can quickly tell us, or model [the thermal performance of the design], and we can accurately cite that innovation and understand where heat gains are*". For 'streamlining process' and 'visualisation/simulation', the positive versus negative experiences were close to equal, while other factors such as 'supporting design thinking and creativity', 'data-driven design and rule algorithm' and 'problem solving', were more associated with negative experiences than positive ones. This was especially true for 'problem solving', where there were 9.09% negative experiences and no positive experiences at all. This suggests that architects do not believe digital tools alone can achieve sustainable design, as one participant stated: "*They're just tools, they're not problem solvers, so they might provide us with the information that we need to make design decisions, but I don't necessarily see them as being the solvers of the problem*".

The positive and negative experiences associated with current and future issues/perspectives identified in the architect participants' responses are presented in Figure 11. From the figure it is apparent that once again, there are more negative than positive experiences in both the future and current encoded content. Of the two, the negative versus positive ratio is higher for the current issues/perspectives (30.23%/16.28% = 1.86) than for the future ones (30.23%/23.26% = 1.30). The reason for the difference between ratios could be attributed to the fact that the external factors include current issues and perspectives such as those related to the client, budget, etc., which are more likely to receive negative responses in general as the participants may easily associate with challenges and barriers involved in the current practice. In contrast, architect participants may need to speculatively discuss future issues and perspectives that may lead to less negative anticipation.

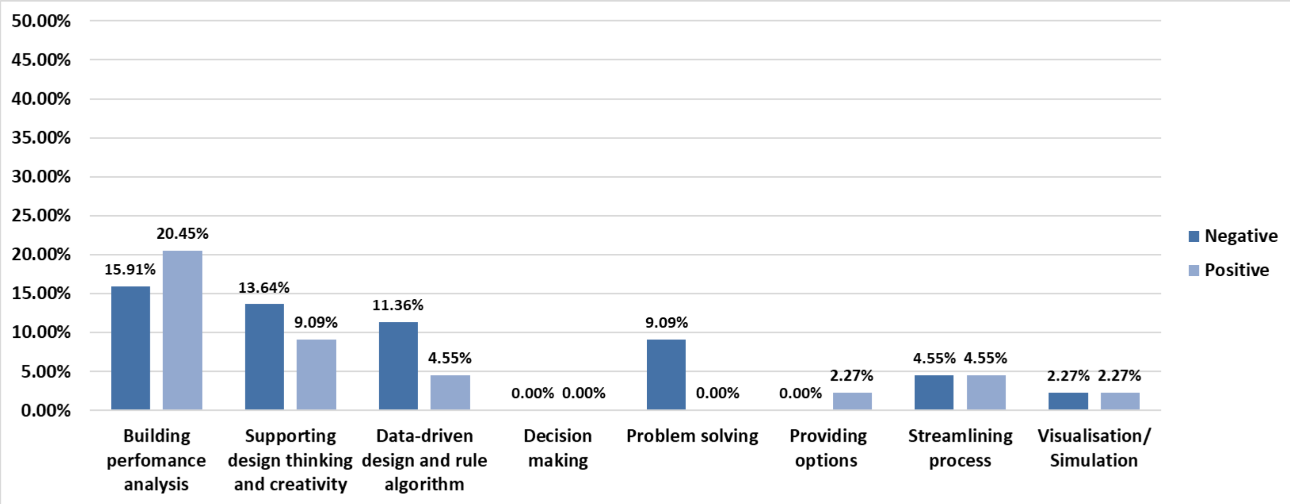

Figure 10. Architects' negative and positive experiences in relation to the factors regarding design cognition.

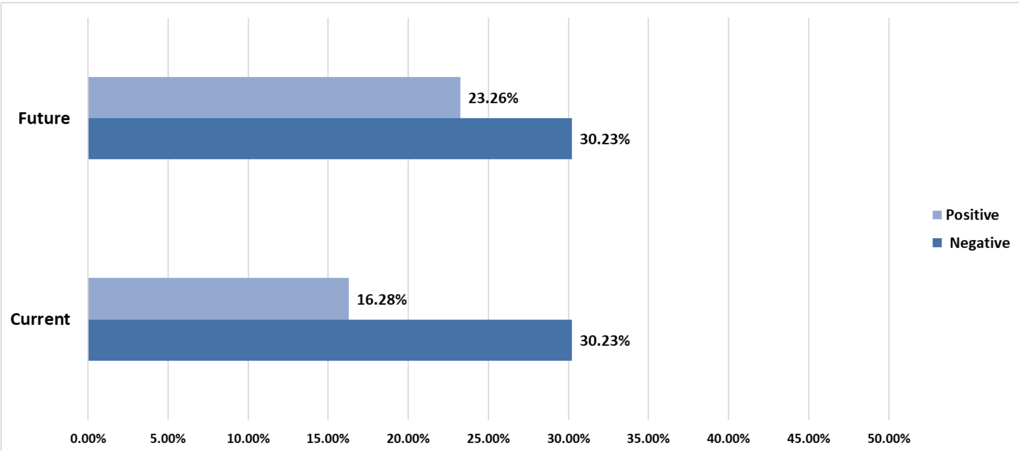

Figure 11. Architects' positive and negative experiences in relation to current and future issues/perspectives as identified in the interviews.

5. Discussion and Conclusions

This study explores Australian architects' perceptions about their sustainable design practices, and the digital design environments they rely on for supporting these practices. 18 architects with appropriate levels of professional experience in Australia were interviewed and the results analysed. The following discussion explores these results.

5.1. External Factors Affecting the Sustainable Design Practices of Architects

External factors, as shown in this study, affect architects' sustainable design practices more than *internal* factors. Such *external* factors include the 'budget', 'client's brief', 'digital design technologies', 'nature of practice', and 'regulation'. 'Budget' is a particularly significant consideration in sustainable design, a view which is echoed by other research that suggests the capital cost of a Leadership in Energy and Environmental Design (LEED) silver certified building is approximately 20–25% higher than that of a traditional building [37]. Participants from our study further identified that "*the level of sustainability is ultimately determined by the client's budget*". Indeed, additional costs for a passive house range between 4–16% [38], and the initial investment in creating a passive house can be recouped within 16–28 years through the lower operating costs [39]. However, a passive house not only benefits from the reductions in energy costs, but also potentially leads to higher quality of the environment and improved indoor comfort for its residents [40]. These broader benefits and incentives need to be communicated to clients to support their budget justification. 'Nature of practice' is another important external factor for sustainable design, as design offices can be operating at different scales and some only focus on the predesign stage without being involved with the detailed resolution of the building; in the latter case, sustainable design is rarely taken into consideration.

Another major factor affecting sustainable design practices is the 'client's brief'. This signals again the importance of engaging the client in discussions about sustainability from an early stage. As participants noted: "*Pretty much every client seems to care about sustainability until they have to pay for it, and then they don't really care about it after that*"; "*Our clients are a wide spectrum of the population and so for some people [sustainability is] really, really important ... , and others we need to lead them*". In many cases, if there is no specific sustainable design related clause in the contract, then architects tend to focus on functional architectural solutions rather than sustainable development (Bonenberg and Kapliński [41].

Participating architects also consider 'regulation' such as building codes to be one of the major factors affecting sustainable design practices, as a participant noted: "*There's an awful lot of greenwash out there ... the regulatory framework is often seen by designers as being exemplary, but the actual principle behind the building codes board, or the minimum standards, is just purely emulating what is practiced, so in other words the energy standards that are the regulatory ones, are not exemplary by any means*".

Our results also reveal that 'digital design technologies' are a significant influencing factor for sustainable design processes. Design tools and media have a significant impact on the processes of the designer [42]; for example, BIM can be used to effectively perform certain simulation and optimisation activities during the sustainable design process to improve building performance, such as achieving better energy efficiency [43]. Participants in the current study highlighted the major digital tools being used in their sustainable design practices, including functional tools that embed thermal modelling into materials in *ArchiCAD* and *Revit*, as well as scripting tools utilising *Rhino* and *Grasshopper*, and specific add-ons such as *Dynamo* for building performance simulation and optimisation.

5.2. Internal Factors Affecting the Sustainable Design Practices of Architects

Internal factors, including architects' 'digital skillsets' and their implementation of 'sustainable design principles', also affect the sustainable practices. In relation to the 'digital skillsets', architect participants expressed significant concerns regarding the time involved in their training and upskilling, and some of them felt that it was not worthwhile, as some participants of this study stated: "*There's always relearning things*"; "*I have to upskill myself a bit, and it doesn't really add a lot of value to what I do*"; "*I think they're great tools but we're not experienced with the actual energy software, other than playing around with them when we're not happy with what consultants have come back with*". There are also some comments received regarding the digital design education architects received from their universities. For instance, one participant mentioned that "*there's rule of thumb that we get taught at university, and then we prove those with a number of digital tools that we can prove glare or shadowing or wind or whatever it is, that we need to test and prove that it actually works*". These results indicate that there may be a need in the future to reflect upon the pedagogy around digital design skills in architectural schools, especially in better connecting with the industry needs.

In relation to the implementation of 'sustainable design principles', participants mainly approached the topic from two perspectives, one being related to architects' knowledge about sustainable design, and the other related to whether architects are willing to implement sustainable design principles in their decision-making processes—in other words, whether they feel it is within the scope of their responsibilities. Our findings are aligned with those of previous studies; for instance, Bonenberg and Kapliński [41] conducted a survey in which their results suggested that there is insufficient knowledge about sustainable development among architects. Similarly with architecture students, Kwok et al. (2014) found that students are not fully prepared for sustainable design in North American architecture schools. This is also supported by Grant [44] who claimed that many architects are not ready to engage in environmentally sustainable design, and that there is consequently a lack of capability to address a range of sustainable aspects of design. Studies suggest that currently sustainability is insufficiently considered by architects during their decision making processes [45]. Architects have an important role in the future of sustainable buildings, such as achieving lower energy consumption, since decisions made during the design phase will translate into large differences [46]. Complicating this, some architects also hold the view that addressing the sustainability aspects of design is the responsibility of an environmental consultant rather than their own [47]. However, although Ecologically Sustainable Design (ESD) consultants are indeed involved in many design projects, nevertheless it is architects who make most decisions about ESD during the design process and it cannot be simply delegated to ESD consultants. This is further reinforced by the fact that "sustainable environment" is now one of the core knowledge domains of the Architects Accreditation Council of Australia's (AACA) National Standard of Competency for Architects. Thus, while ESD consultants do evaluate the design solution to ensure it adheres to minimum standards, fully optimised solutions can only arise when architects properly integrate sustainable design throughout their practices. In an architectural practice there are also other barriers, such as the fee structures, insurance limitations and contractual constraints that may prevent architects from undertaking such responsibilities more comprehensively.

5.3. How Digital Design Environments Support Design Thinking and Creativity in the Sustainable Practice?

Creativity is not just about novelty, but the capacity to challenge the existing paradigms and develop innovative solutions to complex problems, such as achieving sustainability. Typically, scholars in the field believe that digital technologies can enhance creativity [31,48]. Interview results from this study strongly suggest that digital design technologies assist with BPA from a variety of perspectives, which is rational since BPA is a main feature for many sustainable design tools such as *Sefaira*. The second and third most discussed factors within the *design cognition* theme are 'supporting design thinking and creativity' and 'data-driven design and rule algorithm' respectively. Participating architects hold different views regarding how digital environments facilitate design thinking and creativity. On the one hand, they agreed that digital tools can assist creativity to some extent, as evident in one participant's statement: "*So in terms of repetitive kinds of design or just different kinds of forms, it starts to create ... more ideas for architects in ways that they probably haven't thought about before*". On the other hand, they also emphasised that it is largely dependent on how a designer uses the digital tools. As participants stated that "*they need to be used in a manner that help your creative thinking and not hinders it*"; "*it has extreme power and potential for aiding creative processes if you know how to use it right*". These perspectives are encapsulated in a sustainable design practice conceptual model developed on the basis of [30], as illustrated in Figure 12.

The conceptual model illustrates the relationships between the three main themes—*internal* (I_{Deg}), *external* (E_{Deg}) and *design cognition* (D_{Cog})—as well as the associated design environment (D_{Env}) and its support for design creativity (C_{reate}). The size of the circle represents the percentages of coding within the themes developed from the results of this study. From the model we can see that *external* factors account for the most significant percentage (60.62%) during the sustainable design practice, and 'digital design technologies' (D_{Tec}) is the most dominant *external* factor (38.19%) that affect architects' sustainable design practices.

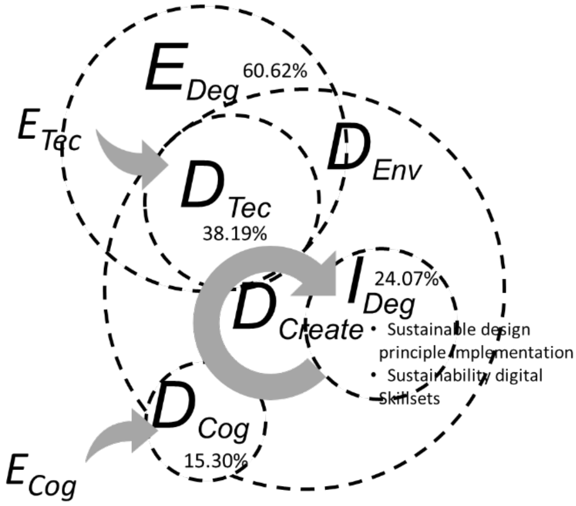

Figure 12. A conceptual model of sustainable design practice developed on the basis of [30].

Other design cognition related factors discussed in the interviews include 'visualisation/simulation', 'decision making', 'problem solving', 'providing options', and 'streamlining process'. Many participating architects believed that 'visualisation/simulation' is a positive incentive for using digital tools. In terms of 'decision making', participants felt that computers can effectively facilitate 'decision making' during the sustainable design process, as one participant put it: "*That's where I think computational design or techniques could be really important, because I think then they might start to give us the facts that we need in order to make decisions*". 'Digital design technologies' such as BIM can store, update and extract building data, and facilitate different analyses to support and improve the decision making process throughout a building's life-cycle [49–51]. Researchers also believe that implementing a BIM approach can enable optimal decisions to be made at the early design stage, by facilitating detailed sustainability analysis using the data available [52]. In relation to 'problem solving', several of the participants commented that in fact digital tools alone are not solving their problems, because it is always the architects themselves who are the ultimate problem solvers even with the support of technologies, as one participant asserted, "*design comes down to a whole bunch of things, which has nothing to do with computers*".

5.4. Conclusions

This study presents interview results with 18 Australian professional architects, regarding their perceptions about, and experiences of, sustainable design practices and the effectiveness of digital tools in supporting such practices. A conceptual model of sustainable design practice has been developed based on the interview results data. The following conclusions have been highlighted from this study.

- Firstly, architects consider that *external* factors such as technologies, regulations, the budget and client, affect their sustainable design practices most significantly. Among the *external* factors, 'digital design technologies' is potentially the most dominant, in light of their current limitations in adequately supporting sustainable design. Other *external* factors such as 'budget' can also significantly affect an architect's sustainable design practice.
- Secondly, architects referred to the term 'design thinking' most frequently when considering sustainable design in the interviews, more than terms related to digital tools. For many participants, digital tools only support architects to make more informed decisions, and do not replace architects' personal experiences or creativity.
- Thirdly, among *internal* factors, architects hold negative attitudes towards their own 'digital skillsets', which is indicative of current computational design skills not being sufficient to support sustainable design. Architects discussed the significant effort and time required for software training, and expressed the belief that upskilling would

not always add value to their practice. Architects also had negative experiences of the implementation of 'sustainable design principles', and some do not consider the implementation of sustainable principles to be their responsibility.

- Fourthly, in term of *design cognition* related factors, architects are relatively satisfied with the capacity of their current digital design environments for supporting 'building performance analysis', and the environments' ability to 'provide design options and alternatives'.

The results suggest that architects most strongly consider *external* factors to affect their sustainable design practices, followed by the *internal* factors and the other factors related to *design cognition*. In general, the participating architects have had more negative than positive experiences towards both their sustainable design practices, and towards the available digital design tools. Several implications can be extrapolated from the results:

- Firstly, there is an urgent need for a critical review of the level of digital design skillsets and sustainable design knowledge available to architects. This can be imparted by architectural education innovation and continuing professional development (CPD), to better prepare the future generation of architects and respond to the UN's SDGs.
- Secondly, the responsibilities of architects for sustainable design during their practices need further clarification and exploration, to better assure that architects would be willing to take responsibilities for sustainable design and to collaborate with ESD consultants more clearly and effectively. In addition, it is also important to facilitate clear and effective communications between architects and clients about the importance and full benefits of implementing sustainable design, to encourage clients to invest in longer-term visions.
- Thirdly, it is evident that digital design environments support BPA effectively, and this is especially the case in recent BIM tools [43]. Such capabilities can assist architects' decision making in sustainable design; however, the effect and benefits are also largely dependent on how architects use the tools, since digital tools alone are not the problem solvers.

These results and their implications suggest that the task of producing optimal sustainable design solutions lies firmly within the realm of architects, both in terms of their knowledge/capabilities and their ability to effectively utilise digital tools. The study also provides opportunities for reflection about future improvement of sustainable design and digital technologies, from various perspectives including the support for design thinking and creativity, data-driven and rule/algorithm-based design, and design problem solving. More recent digital technologies such as generative and parametric design have shown much potential, and their features could be developed further to better support sustainable design practices from those areas.

As the scope of this study is focused on the Australian context and the results were derived from semi-structured interviews with 18 professional architects, we are cognizant of the limitations of the sample size and location, while considering the generalisation of the findings. Future extensions of this research will consider: (1) Expanding the scope within and beyond Australia, as well as encompassing cognitive studies of architects' sustainable design processes for better complementing, contextualising and generalising the findings. (2) Enlarging the sample size to obtain more statistically significant results. (3) Further validation of the developed sustainable design practice model using case studies of existing sustainable design projects. (4) Exploring the impact of emerging digital technologies such as machine learning [53] for supporting sustainable design practices.

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