Computational Design Sustainability: A Conceptual Framework for Built Environment Research

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This paper presents and demonstrates a “Computational Design Sustainability” (CDS) framework, inspired by “Computational Sustainability” (CS), which is a new area in computational research (C. Gomes & Yang, 2011). CS aims to apply techniques from computer science to address sustainability problems affecting a wide range of fields from environmental sciences to social studies. While CS has been broadly embraced in environmental science, the great potential of this concept to address grand challenges and solve complex problems seems to have not been adequately explored in the built environment domain. Therefore, this paper attempts to formally investigate the application of CS in built environment research addressing different scales of design problems with computational design through proposing the new concept of CDS. These approaches are demonstrated and evaluated through a range of projects collectively conducted by the research team. CDS proposes to advance computational design research by creating a trade-off between pillars of sustainability in an integrated multifaceted and multidisciplinary approach. The presented conceptual framework provides a formal means to critically understand and further advance these approaches in a systematic way suitable for future development and broader application.

**Keywords:** Computational Design Sustainability, Computational Sustainability, Computational Design, Sustainable Development, Built Environment Research

INTRODUCTION

As a result of high consumption of natural resources and increased CO2 emissions in the last century, the human subsystem can be considered a major component of the overall ecosystem, so much that a new geologic epoch called “Anthropocene” has started (Daly, 2005; Steffen et al., 2007). In this context, the long-term goal shifted from growth implies an increase of quantity or size, to development, that suggests an improvement in quality (Costanza, 2020).

This rapid change of contemporary, social and urban scheme, concurrent with the responsibility of issues related to sustainability intensifies the need to develop solutions and adapt to the ongoing changes...
(Fox, 2009). In the built environment domain, this calls for innovative approaches and technologies that enable a shift from individual to collaborative, disciplinary to interdisciplinary, and implicitly to explicitly managed design processes (Haidar, Underwood, & Coates, 2019). Such design processes attempt to come up with scalable solutions beyond mere computational processes, inspired by real-world problems (C. P. Gomes, 2009).

Computational sustainability (CS) adopts techniques from computer sciences to address sustainability problems (C. Gomes & Yang, 2011) while affecting a wide range of areas, from environmental science to social studies, only recently started to explore fields such as smart cities development (Simonetti & Birch, 2017). In the design and built environment domain, emerging computational methodologies, such as parametric design, are indeed representing the potential for supporting sustainability. However, considering the speedy advancement of technology and its impact on computational sustainability, such potential to address grand challenges and solve complex problems seems to have not been adequately explored in an integrated, collaborative and multidisciplinary approach. This approach can be explored in Computational Design (CD) due to inherent nature to engaging computational thinking as well as innovative technological capacities (Celani & Veloso, 2017; Oxman, 2006). CD has been altering the traditional ways of conducting research and design activities while addressing multi-faceted complexed issues in the built environment.

Therefore, in this study, we apply and extend CS in a design context to explore the question “how computational design approaches in built environment research enable and advance sustainability?” Mapping the two concepts of CS and CD, the aim of this paper is to introduce, define, and demonstrate “Computational Design Sustainability” focusing on the key conceptual components, methodological approaches, and implementations within the built environment discipline. More specifically, we are interested in formally understanding how the applied methods in computational design can benefit sustainability. Through a critical literature review, the paper will focus on the key terms and issues of the topic considering different scales of built environment research, varying from individual buildings to urban scales. The presented conceptual framework provides a formal means to critically understand and further advance these approaches in a systematic way suitable for future development and broader application. In other words, it can assist in identifying new research directions, methodological approaches, potential applications (i.e. analysis, collaboration, management or generation), and also finding the available computational techniques connecting to CD. This framework is demonstrated and evaluated through a range of projects collectively conducted by the research team.

**COMPUTATIONAL SUSTAINABILITY**

Computational Sustainability (CS) (C. Gomes & Yang, 2011) is a novel research field that attempts to employ computer science technologies such as Artificial Intelligence and Machine Learning to address broad sustainability problems integrating environmental, economic and social dimensions. These problems in CS are classified according to the relevant computer application that is utilized to address the problems (C. Gomes & Yang, 2011). As such, common categories of the research field in the CS framework includes computational simulation, constraint optimization and machine learning, data mining, planning control and scheduling, policy and action learning. Since the nature of such problems is complex and concerns various disciplines, they often require multidisciplinary approaches (Silva & Analide, 2019). Computation and sustainability arguably move each other forward while adapting methods and mathematical models developed to solve one problem to tackle another problem, even transferable and scalable across various disciplines (Eaton, Gomes, & Williams, 2014; C. Gomes, 2019). This framework has been mapped to different problems solvable by various computational methods.
As an example, many computational approaches have been developed to tackle issues that involve environmental concerns and resource management with economic and corresponding social problems such as poverty. Rapid population growth concurrent with the high-speed consumption of natural resources has amplified the need for solutions to tackle the growing problem of poverty. However, lack of data and high cost of the available social data such as census data has triggered motives for CS researchers to employ machine learning methods and using satellite and remote sensing data technologies to extract socioeconomic data in a less costly and faster way. This approach has facilitated the process of data collection in some countries where access to such data sources is difficult, demonstrating the effectiveness of computational and multidisciplinary methods in addressing sustainable issues (C. Gomes, 2019).

While CS has been embraced in environmental science and is being broadly applied across other disciplines, the effective application of the available computational techniques and tools to integrate sustainability in built environment design research, however, remained unclear. Such methodologies can be explored in Computational Design (CD) due to its innate nature to engage computational thinking to innovative technological capacities (Celani & Veloso, 2017). The next section introduces CD and the key concepts underpinning it.

**COMPUTATIONAL DESIGN**

Influenced by the 1960’s new systematic methods related to Design Methods Movement (Celani & Veloso, 2015; Rocha, 2004) and the cybernetics theory (Menges and Ahlquist, 2011), computers have been introduced in the architectural field as a novel way of understanding architecture through computing using an explicit, systematic design process (Eastman, 1973; Mitchell, 1975).

Computational Design (CD) is the approach in which design problems are explored through computing regarding the creative process, evaluation, analysis, interaction, aesthetic, and presentation. The term is closely related to the earliest understanding of Computer-Aided-Architectural-Design (CAAD) (Mitchell, 1975) and Design Computing (Gero & Maher, 1999), refereeing to process computing information towards a design. It can be wrongly associated with Computer-Aided Design (CAD) systems as a computerisation process (Terzidis, 2006), or in other words, as digital drafting tables. Computerisation and Computation differ in the design process, where the first is the literal translation of the conceived design to a new platform, which means not altering the amount of information produced during the process. The latter establishes interactions between information and design elements through an algorithmic process, by increasing the amount of information that was given as an input, contributing to adding new information to the design process.

In the last decades, with the advent of embodied script languages in Computer-aided Design (CAD) and Building Information Modelling (BIM) software as well as their visual editor of algorithms, such as Grasshopper and Dynamo, CD became popularised among architects and scholars (Burry, 2013; Celani & Vaz, 2012; Oxman, 2006). This has empowered designers to do scripts in a more user-friendly platform and explore a unique refinement of the design problem-solution with an entire family of possible solutions that are based on the same principles and design rules (Burry, 2013).

CD offers a wide range of applications and computational techniques in tackling a variety of design problems, however, the link between CS and CD has not been systematically defined and explored in the current literature. The following sections attempts to instigate bridging the gap by mapping between the two themes and understanding the mutual contributions of these fields.
EXPLORING COMPUTATIONAL DESIGN SUSTAINABILITY

Methodology
Through reviewing existing literature in built environment research, this paper seeks the answers to the following questions:

• How CD can help deliver a more sustainable solution integrating different aspects of sustainability?
• How CDS can be defined within the realm of built environment research and practice?

Firstly, a thorough literature search and review has been carried out to establish an understanding of the current state of the topic and to identify the gaps of knowledge. Web of Science was the main database for this research, along with CumInCAD database - which covers key conferences and journals in the field of CD. To limit the search protocol, the filter was set to cover papers in the past ten years, all in English. The time limitation was proposed due to technology development, in order to keep all papers consistent with current technical knowledge. Using variations of “sustainab”, “design” and “computation” as keywords, 354 records were found and, after the title and abstract screening, 26 of them were identified as relevant. Afterwards, with the tendencies assessed and the range of possibilities for improvement of sustainability analysed, a framework was introduced to demonstrate and exemplify the necessary points for a built environment sustainable approach.

Overall, while the literature search showed that the term, CDS, has not been utilised or introduced by any research paper to the date of conducting this study, the suggested framework of CDS in this paper details out the CS concept by focusing it on the built environment research. The following sections attempt to explore and define it within the built environment research and explicate the results of the literature search in more detail.

Results
In order to understand and analyse the range of approaches used to introduce sustainability to design, the selected papers were categorised according to several components. These components include the main computational themes the papers employed and sustainable aspect they addressed along with the computational techniques within the relevant computational theme, and application of the methodology. Further refinement was applied to identify which life cycle stages are more studied and have more potential for the application of CD methods in two major scales of building and urban. The results are reported in Tables 1 (building scale) and 2 (urban scale).

From Tables 1 and 2, some important tendencies, as well as critical gaps, are evident. Overall, out of the 26 selected records, only a few studies integrate all or more than one aspect of sustainability. Those of which are mainly focusing on the environmental aspect, such as building energy performance studies on building scale (Smith & Lasch, 2016), and sustainable form generation in urban scale (Cassiano et al., 2018), with little or no integration of economic and social sustainability concerns. The focus on environmental impacts was expected based on the common misconception of what sustainability encompasses; nevertheless, it is important to emphasise the relevance of all pillars and the interrelation between them.

Table 1
Building scale
In terms of the stages that these studies are commonly targeting, design and performance are the most studied ones, especially in the urban scale. In the building scale, taking advantage of BIM technologies, the involvement of more life cycle stages was more feasible due to the capability of BIM tools to engage information from different parts and across different disciplines. However, the reason for the lack of studies covering other stages may need to be further examined through the existing computational techniques and to see whether it is due to the limitations of the current applicable CD methods. Regarding the CD, the utilization of the themes also is not even across the various CD themes with having parametric design as the most employed one in both urban and building scales.

The insights from Tables will be further explained through introducing the concept of CDS in the form of a conceptual framework in the next section.

**DEFINING COMPUTATIONAL DESIGN SUSTAINABILITY**

To introduce CDS, as a field that bridges multidisciplinary approaches in built environment research, this study has developed a conceptual framework that intends to show i) how CDS can help develop an integrated approach while balancing sustainability pillars, ii) how CDS can be an interdisciplinary and collaborative field, and iii) how CDS can advance knowledge in both computational design and sustainability.

The framework has been established based on the existing knowledge around CDS and categorises the relevant concepts while indicating their relationships. It summarises current approaches that employ computational techniques to overcome sustainability problems in design research. In addition, it interrelates different themes based on the overlapping of concepts shown in Tables.

As indicated in the illustrated framework, and mentioned in the paper, sustainability studies are based on three established pillars of environmental, social and economic. To show the integration between them, as well as emphasize the need for multidisciplinary studies, the proposed framework refers to sustainability themes as the socio-environmental approach, socio-economic approach and environmental-economic approach.

Regarding CD themes, according to Caetano, Santos, and Leitão (2020), existing approaches can be divided in the three categories, namely Parametric & Algorithmic design, Generative design and Performance-based design. In addition, based on the studied papers application within sustainable design research, which are conducted in various life cycle stages, a combined category is provided. Sustainable form creation covers project stages, from planning to design; sustainable performance denotes the completion and efficiency of the studied built environment, with applications usually being made before the actual construction to achieve optimal design; and, sustainable management referring to the management considerations and processes which normally encompasses whole life-cycle stage.
To demonstrate the concept and elaborate on the proposed framework, examples of current projects within the CDS field being conducted in our research group are presented in the following sections (Figure 1). These projects, which are ongoing PhD research projects, can exemplify the potentials in developing collaborative, multidisciplinary and integrated approaches from a wide range of research fields, namely waste management, place making, urban density, and heritage planning. The common aim of these projects is to tackle a trending sustainability problem in the design domain utilising a broad range of CD methods and approaches.

**Sustainable management with parametric BIM**

In a whole-building level, researchers commonly use BIM-enabled tools to address environmental problems through the design or performance stage (Ayman et al. 2019). Yet, there are still some gaps related to Construction and Demolition waste (C&Dw) care and disposal, even though it can represent almost 40% of a country’s total waste. While there are several waste management techniques available, prevention at source is seen as the most sustainable option (ref). However, from a building’s perspective, there are some inherent characteristics that need to be encompassed, such as a large number of materials and stakeholders involved, the high lifespan and the range of possible scenarios and options during the life cycle of the building, which requires a process that can manage information to support decision-making in a straightforward approach. Hence, a multistage model is being developed by the research team, with the use of BIM technology, to design out C&Dw, meaning to avoid waste during the design stage based on its final environmental impact. The proposed methodology analyses and acts on different life cycle stages through the design stage, aiming to improve the overall sustainability while involving multiple stakeholders.

The CDS diagram came early in assisting this research during problem formulation. Based on it, the authors have had a broad perspective of the field and their own approach. For instance, the diagram has helped to identify the potential parametric design techniques applied to develop optimal solutions. Such solutions become essential, not only to reduce environmental impacts but also to lower costs since a good percentage of the overall C&Dw figure is predetermined during the design stage (Baker-Brown, 2017). In this sense, the research has a strong inclination to an environmental-economic approach through a sustainable management concept. However, as a by-product, a social approach will also be conducted due to the analysis of users’ behaviour and stakeholders’ patterns towards decision-making processes that influence the final environmental impact related to waste. With the CDS framework, the authors have been able to identify the potential gaps by having a wider view of the various aspects of the research problem concerning waste management in building construction. The next sections demonstrate the applicability of the CDS framework in research projects within an urban scale.
Sustainable form creation with generative design
In recent years, the smart cities’ concept has started to become part of the sustainability agenda (Bibri, 2019) as researchers are exploring new ways of dealing with the interrelated future cities challenges, such as rapid urbanisation, climate change and resource scarcity (Albino, Berardi, & Dangelico, 2015; Bibri, 2019; Schwab & Buehler, 2018). The research team are developing an integrated design approach to generative form creation and smart technologies. Sustainable urban forms have been generally neglected on smart city’s literature, while the integrative approaches that could better connect the urban design professionals to smart technologies are lacking as well. Being that, designers’ daily decision-making process, which is often based on intuition, could be enhanced using smart technologies, enabling new possibilities of form creation through a generative data-driven approach. Generative design approaches have shown the potential as creative and integrative design in recent years (Caetano et al., 2020), representing new ways to explore unknown paths of the design solution space through the creation of a design system. Generative design approaches can shift the paradigm of the decision-making processes from intuition-based design practices to data-driven urban design sustainable approaches.

This research project proposes the utilisation of generative design methods to better explore new ways of understanding people’s activity and their perceptions about the surrounding environment. It also aims to explore design solutions of a physical context regarding the quality of the urban environment and the urban placemaking process, integrating urban placemaking, smart technologies and generative design tools for sustainable form creation. The CDS framework has helped this project on the research conceptualisation since it provides a structure of a broader understanding of computational methods involving sustainability, correlating essential aspects of the field. Therefore, the theoretical and methodological decisions of this project have been enhanced through the CDS framework, contributing to the conceptualisation as well as the systematisation of methodology.

Sustainable performance with performance-based design
As illustrated in the CDS framework, one of the integrated approaches is the performance-based design to achieve sustainable performance, which can be reflected in multiple dimensions of sustainability, including socio-environmental. An example of this research approach is a computational model that is being developed in the research group, aiming to capture the relationship between compact city urban strategy and its social impact. Referring to the shortcomings of many of the allegedly sustainable projects in balancing all pillars of sustainability, they argue that the urban density strategy, which is generally known as sustainable development, does not adequately involve social aspects as much as other pillars of sustainability. The research project proposes the utilisation of computational design methods to better understand the role of design in the relationship between density and social sustainability to achieve sustainable performance. These methods integrate spatial analysis using building and street networks to give a spatial dimension to defining density in the form of ‘spatial density’. This integrated approach has been so far proven to be effective in correlating some aspects of design, density and social sustainability (Soltani et al., 2019), while the project is still ongoing.

Referring to the CDS framework, this research has benefited from the proposed concept by enhancing the structure of the study, offering a coherent conceptualisation of the research by systematically defining the essential aspects of the field. This, in turn, can lead to providing a trade-off between aspects of sustainability by attending the research problem from an interdisciplinary approach whereby a profound understanding of the interplay between multiple issues, being social sustainability,
urban density, and design is possible by means of CDS framework.

**Sustainable performance with performance-based design in heritage planning**

Sustainable heritage planning is another topic being studied by the research group aiming to achieve a sustainable performance for the historic town using CD techniques. Historic towns present a precious legacy for contemporary society that embodies how humans use the spaces enveloped within human settlements (Liao et al., 2019). However, the unbalancing development of heritage tourism has often led to the dramatic spatial and functional transformation of historic towns that cannot be overlooked regarding planning a sustainable town, which should emphasise not only the economic aspect but also the social, cultural, spatial and functional aspects. The research project utilises a computational approach that is not widely used in conventional heritage planning, where sustainable performance has been addressed.

In this study, quantitative techniques that mainly include parametric and algorithmic designs are utilised to integrate and analyse the spatio-functional patterns of historic towns as well as the correlations between the spatial configurations and land use distributions to improve the sustainable performance. The computational approach is used where it has been proven effective, automate and robust. The preliminary results have shown how a historic town can conserve the spatial spirit and optimise the functional distributions, so a more sustainable form can be achieved using such an integrated computational approach. Returning to the CDS framework, the topic of heritage planning has been expanded using a computational methodology. It provides a solid umbrella for performance-based design projects, offering computational techniques that may enlighten researchers who are interested in the sustainability research projects.

**CONCLUSION**

While CS has been broadly embraced in environmental sciences, few studies have employed CD to tackle emerging sustainability problems in an effective and integrated manner in the design and built environment domain. The paper has proposed an integrated approach through CDS, which brings CD and sustainability together to address the multifaceted problems within the built environment research. Furthermore, our literature search and review showed that the concept of CDS has not appeared in other research papers, and hence, is not well-established and well-studied in the current field.

In this paper, we drew attention to the great potential of the CD approaches in addressing sustainability issues within built environment research. The main contribution of the paper was to provide a comprehensive and integrated framework of CDS, introducing its definition, scope and approaches in which current existing research of CS and CD can be well embedded. The proposed framework extends the CS with the context of design and allows for identifying new directions in built environment research.

It was also demonstrated that CDS is arguably beneficial for identifying the potentials of applications within the computational design realm. It can help understand design and evaluate computational design research with a sustainability focus. The framework enables multidisciplinary research where sustainability is linked to computational approach and associated techniques. It offers conceptualisation regarding different aspects of computational research so each phase can make use of the concepts and related methods to advance the CDS research.

The CDS framework has been demonstrated using the research team’s ongoing projects and revealed how the framework can be applied and tailored for addressing different design sustainability issues ranging from buildings to urban scales. Consistent with the scalable methods in the original CS concept, the CDS framework enables scalable solutions across different disciplines and repurpose them to design and built environment research. The frame-
work critically reflects the current trends in the research field and guides future advancement with a broader and integrated application. That is, it facilitates for researchers and practitioners to start capturing and exploring new directions in CDS suitable for future developments as well as providing a communicative platform, facilitating a more systematic and formal research planning.

Due to the limited search sources, search keywords and years, we have not included every single available computational approach in the built environment as the focus was only limited to the common and generic computational themes and techniques in the computational design research. Furthermore, to confine the scope of the study, the literature search only focused on the academic papers and did not include the practice-based experiences in the current investigation. Also, we did not search through the themes under the framework individually and separately, which all require future work.

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