Review

A Critical Review of Computational Creativity in Built Environment Design

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Abstract: Computational creativity in built environment (BE) design has been a subject of research interest in the discipline. This paper presents a critical review of various ways computational creativity has been and can be defined and approached in BE design. The paper examines a comprehensive body of contemporary literature on the topics of creativity, computational creativity, and their assessment to identify levels of computational creativity. The paper then proceeds to a further review of the implications of these levels specifically in BE design. The paper identifies four areas in BE design where computational creativity is relevant. In two areas—synthesis (generation) and analysis—there is considerable literature on lower levels of computational creativity. However, in two other areas—interfacing and communication—even the definition of computational creativity is not as defined and clear for the discipline, and most works only consider the role of computers as a supporting tool or medium. These open up future research opportunities for the discipline.

Keywords: computational creativity; human–computer (co-)creativity; creativity support tools; built environment design

1. Introduction

As the use of computation and artificial intelligence has increased in built environment (BE) design, their roles in supporting creativity, a quintessential quality of design, have been examined more frequently [1–4]. Each of these topics—computation, creativity, and design—features numerous aspects and thus, formulating and assessing them in combination have resulted in various methodological and systematic approaches. A particular issue in combining these topics is that they harbor different viewpoints and perspectives of different disciplines. Computational creativity, for example, has usually been approached as the creativity of an individual computational agent in most disciplines, i.e., artificial intelligence (AI) and cognitive science [5], while BE design is often viewed as a collaborative or team activity [2]. Therefore, understanding current research foci and approaches to creativity, computation, and BE design is significant for establishing the research foundation of computational creativity within BE design.

This paper will present a critical review of computational creativity in the BE discipline with consideration of computation, creativity, and BE design. To this end, this study first examines definitions of creativity, including creativity in general, computational creativity, and human–computer co-creativity to categorize these three formal approaches to defining computer-related creativity. In the same section, methodologies to research and assess each approach are discussed. The paper then focuses on different applications of computational creativity in BE design.

2. The Method

The focus of the present paper is on computational creativity in BE design. However, in order to maintain a feasible scope for the research, the first part of the critical review (Section 3) is based on the comprehensive findings by including contemporary publications [6–11] with

the respective foci of individual components, namely, defining and assessing both creativity in general, and computational creativity, rather than revolving only around the narrower topic of computational creativity in BE design. These provide a feasible scope with adequate breadth to set the foundation for the specific review of the second part. The main sources for reviewing these individual components are listed in Table 1, supplemented by the fifteen other relevant resources.

Table 1. Main sources used in the first part of the review (Section 3).

Research Topic	Source	Year	Notes
Assessing creativity	Said-Metwaly, Kyndt and Van den Noortgate [6]	2017	Creativity in general
	Jordanous [8]	2016	Computational creativity
Computational creativity	Kontosalo [7]	2020	Each provides categorization and identification of the aspects and levels of the computer's input to creativity
	Davis [9]	2017	
	Colton, Pease and Cornelli [10]	2015	
	Hoffmann [11]	2016	

For the specific review on the computational creativity in BE design (Section 4), the framework of that section is based on a publication by Lee, Ostwald and Gu [2] on design (thinking) in the BE discipline. Afterwards, the subsections have been developed based on sixty-two main sources retrieved from different academic databases, by applying relevant sets of searched keywords for each subsection. Of these sources, around thirty pertain to case studies or applications of reviewed methods. This is an emerging topic; therefore, many of the identified sources are conference or workshop papers, reporting on ongoing research.

3. Three Critical Approaches to Defining Computational Creativity

Creativity, or the ability to create, has historically been considered a faculty of intelligent living beings such as humans, or deities and muses in religion and literature. However, the advent of computers with their "artificial intelligence" and generative mechanism has raised new questions and debates on the nature of creativity, especially when the "mindless" device is itself involved. In this section, three approaches to defining and reviewing computational creativity are discussed in this regard. They are: (1) creativity in general, devoid of necessitating computers; (2) computational creativity (CC) where computers are the "creators"; and finally (3) human–computer (co-)creativity (HC^3) that pertains to the collaboration or cooperation between computers and humans in producing creative outputs. This section first defines creativity in each approach, then provides a review of methods for formally studying them.

3.1. Defining Creativity
3.1.1. Creativity in General

Creativity, in general, is usually defined not by what type of activity it is, but by the qualities of its outputs. The most common of these qualities are novelty and value. The former quality refers to a sufficient difference from the earlier products in its context, and the latter accounts for the utility of the product [12]. Both qualities can be expressed by alternative terms. Novelty can be replaced by terms such as "authenticity", "uniqueness" and "originality" to describe that difference from existing products [13]. The novelty of the product can be relative to the context of the creative process. Historical (H-) creativity is when the product is considered creative by a large number of people due to its "global" novelty. This is exemplified by, for example, art masterpieces with a wide recognition. In contrast, personal (P-) creativity occurs within the scope and context of the creator. In this case, the product is new or original relative to the knowledge of the creator. This form of creativity is interesting because it helps understanding the internal cognitive processes leading to creativity [14].

The definition of the second quality, value, may vary by discipline (e.g., aesthetically or functionally utile); therefore, it is also described by terms such as "appropriateness" and "usefulness" [13,15]. Another quality that has become a common component of the definition is surprise, which is defined as a defiance of expectation [12]. Hence, a concise definition of creativity is the ability to produce something novel, valuable, and surprising.

The study and assessment of creativity, however, expands also to other aspects of creativity. A common categorization of these aspects was proposed by Rhodes [16] and other scholars, reviewed by Jordanous [8], who identified four "perspectives" of studying creativity. They are, namely, person (or producer), process, product, and press, collectively known as the Four Ps. The first P, person, represents the producer(s) whose personal characteristics may influence their creative potential. Although there were earlier studies which pinpointed several characteristics as influential, later studies were not conclusive [6]. The creative process includes behaviors and tasks which lead to the generation of the creative output. The press is the environment or context surrounding and interacting with the person. It usually accounts for the social aspect of creativity where a creative output or person is received. However, it may also be represented by a team of collaborative creators.

3.1.2. Computational Creativity

When the producer or person is a computational agent (or software), then its creativity is commonly termed as computational creativity (CC). In other words, CC is often approached as an automated variant of human creativity [9]. However, literature varies on the focus of the automation. One common approach is to define CC as automating the production of a creative product, regardless of the process involved to create such a product. This contrasts with trying to emulate cognitive creative processes or tasks by computational means [17].

A problem for either definition stems from the history of applying creativity. For millennia, creativity, as a topic and term, has been only applied to humans and other living creators [5]. Even after the invention of computers, it took decades for the machine to reach a potential to produce something which could be regarded creative by loose standards. This gap in success, termed as the "humanity gap", has had significant consequences on studying CC. This difficulty of formulating a human-like creativity for computers has persuaded the focus on the product among the Four Ps that is the easiest to assess and compare between humans and computers [10].

As a result, the assessment of CC has also been often limited to assessing the products, a fact which creates several challenges. Firstly, the timing and scope of assessment can influence the interpretation of the scores. While creative products are generally judged in their final state, their creative component might have partially been applied earlier [18]. If there are multiple creative agents and stages during the process, their contribution may not be evaluated and accounted for accurately without tracing different stages and ideas over time. This brings us to the second challenge. Historically, study of creativity in both cognitive sciences and AI disciplines had a relatively narrow focus on the creativity of the individual mind or agent. This individualism seems to stem from the fact that most artists and famous creative geniuses appear to have created their works single-handedly [8]. There was usually one Picasso or Michelangelo working on a painting, one Mozart or Beethoven on a musical piece, or one James Joyce or Shakespeare on a play. However, creativity is hardly a stand-alone individual phenomenon. It has both social aspects (press) and is collaborative in many disciplines such as design.

Collaborative and interactive approaches to CC were increasingly recognized and studied in the 2010s. The expectation of automation and individualism from a creative agent has limited CC to only those situations when the interacted software is largely autonomous in its generative process. This limitation has created a gap between studying human–computer interactions (HCI) and CC [11]. Nevertheless, contemporary studies have assumed collaborative or interactive roles for computer software [7,9,11,19]. There are different implications for denoting the combined input of humans and computers

for a creative output; computers can be supportive, collaborative, co-creative, etc. Here, an "umbrella" term of human–computer co-creativity is considered for further discussion in this paper.

3.1.3. Human–Computer (Co-)Creativity

Human–computer (co-)creativity (HC^3), as coined by Hoffmann [11], is a form of co-creativity in which there is at least one human and one computer creator. Co-creativity itself is defined as a creative setting where multiple parties contribute to the creative process with each having creative inputs [20]. Therefore, a common expectation from a co-creative computational agent is that its creativity is comparable to that of its human "colleague" [21], providing similar input as the collaborating human. However, this simplification of the co-creative role risks falling into the trap of the humanity gap. Hence, it is necessary to carefully examine more diverse roles and modes of participation by computer agents with humans in a creative process [7,9].

One approach by Hoffmann [21] considers computers as information (processing) systems. He presented three ways such a system can influence creativity. The first method is by modelling or exploring the design space to boost the novelty and divergent aspect of creativity. The second way is book-keeping or evaluation, in which computers analyze products for their originality and/or value. Finally, the computer facilitates or participates in communication between the design team or design tasks.

Another approach is summarized by Davis [9], featuring three categories of roles played by computers. They include creative support tools (CSTs), generative algorithms, and as human-like colleagues. CST includes tools such as computer aided design (CAD) software that provide an open-ended space for humans to explore. These tools can assist the human by supporting or boosting the person's existing abilities, training them to acquire new experiences and skills, or enabling them to perform otherwise impossible new tasks. In any case, CSTs have not usually been regarded as proper examples of CC due to the lack of creative input by the computers themselves. The second category, generative agents or algorithms, includes (semi-)autonomous producers that generate products mostly on their own. They may also have evaluating mechanisms to ensure the value of the outputs. They may, however, lack interactive capability during the generation with either the human user or their problem environment, and instead rely on their extensive knowledge base. This property distinguishes them from the third category, the "colleague", which interacts and communicates as well.

Kontosalo [7] breaks down the former categorization into seven further roles of the computer agents. The first three supportive roles reflect the three types of CST: support, training, and enabling. However, she does not categorically distinguish between generative and collegial roles and lists both under the computer colleague category. A computer colleague may generate or evaluate products, find problems/solutions, and control initiatives within the creative process.

The questions of what role amounts to the creative, generative, or supportive can reflect back to the perspectives of creativity (the Four Ps). If the co-creative team is viewed as a collection of discrete individuals, then identifying CC may depend more on the human-like creativity of the computer agent which would be a person on its own. On the other hand, assessing CC would lean towards considering various creative contributions of the computer agent to the whole of the team's creative process if the team is considered a collective unit.

3.1.4. Summary of the Role of Computers in Creativity

As far as the role of computers in creativity is concerned, the literature points to three levels of creativity—CC, HC^3 and CST—relative to the independent creativity of the computer (Table 2). To further interpret the role, these three levels are contextualized in relation to human creativity (Figure 1). The first two levels correspond to computational creativity (CC) and human–computer (co-)creativity (HC^3), which have been introduced

above. The most independently creative level is CC. It is also termed computational creativity proper where the computational agent is the creator, comparable to a creative person (Figure 1b). Theoretically, it can also collaborate with humans or other similar computer agents (Figure 1c) in the sense that they share the same goal and participate to achieve it together. In the next level, HC^3, the computer agent interacts with human agents in the creative process. Although originally, this term was applied to a person-like artificial colleague similar to CC, (Figure 1c), contemporary literature also considers less powerful or automated agents such as generative systems undertaking partial tasks in the overall creative process. In this regard, the computer is less involved in the whole of the creative process and mostly cooperates with humans in the creative process by co-sharing creative tasks (Figure 1d). A lower-level creative role also exists as creative support tools (CSTs), where the computer does not produce on its own, and largely or only supports human creativity (Figure 1e). CST, first categorized by Davis and also reviewed above, constitutes the third level.

Table 2. The three levels of computational creativity: computational creativity (CC), human–computer (co-)creativity (HC^3) and creative support tool (CST).

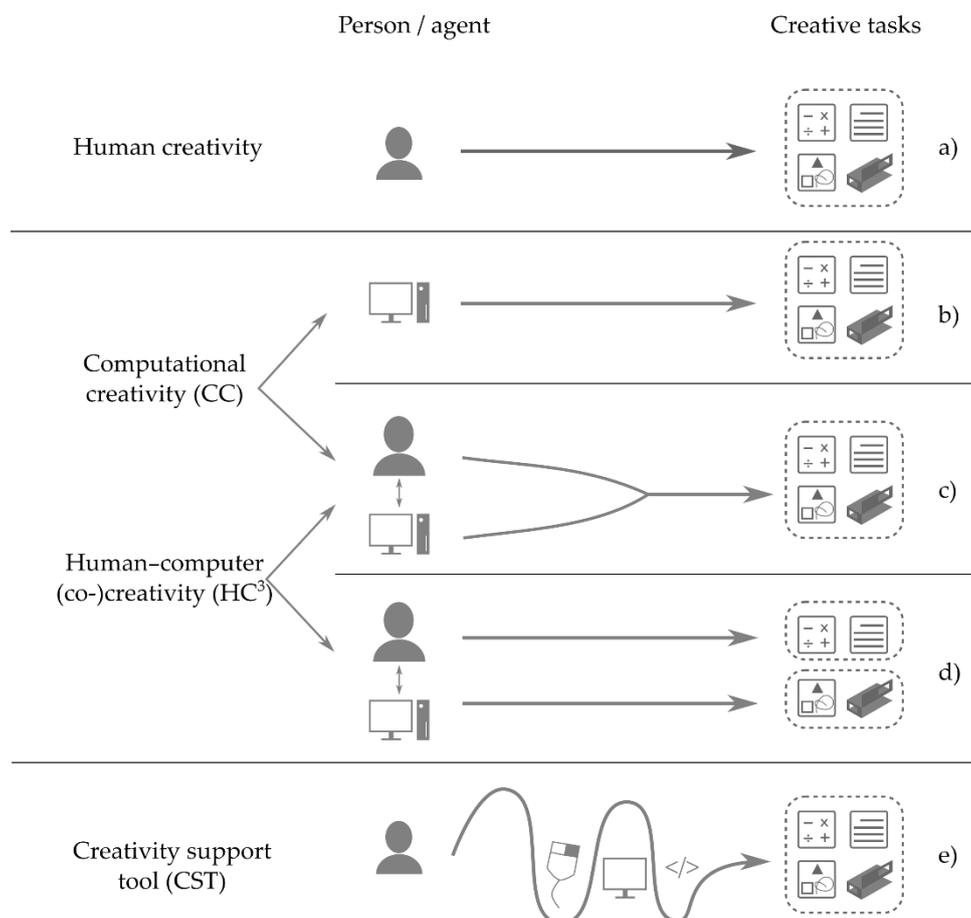| Levels	Relationships to Creativity	Interactions with Humans
CC	Independent human-like creation	Individual or collaborative creation
HC^3	Performing partial creative tasks	Interacting with humans
CST	Providing tools and environments for human creation	Mostly supporting humans for realizing their creation

Figure 1. The relationships between humans and computers in the three different levels of computational creativity (CC, HC^3 and CST).

3.2. Methodoligies to Assessing Creativity

3.2.1. Assessing Creativity in General

As mentioned, the Four Ps are a widely accepted categorization of approaches to assessing creativity. Among them, the product is the most common and recommended focus of the assessment. Assessing creativity in the product is usually conducted with a consensual assessment technique (CAT) that employs a panel of judges who are usually experts in the product's domain. The panel usually uses a set of rubrics, which may include different expected qualities of a creative product, and provides the scores based on a scale for each product in comparison with the others. In addition to the relevant skills of the panel, the strengths of this method are the ease of its application and its independence from theoretical discussion about creativity. However, the subjective nature of this assessment can create challenges for its robustness. For one, the judges' opinion and level of expertise can result into inconsistent scores. Furthermore, their potential lack of knowledge about the background of the creators may makes it difficult to assess the P-creativity of the producer or team.

Assessing the creative process usually involves studying the cognitive process which results in a creative output. Said-Metwaly, Kyndt and Van der Noorgate [6] point out that the common assessment method is to test the divergence ability of the creators, or to examine the quantity or diversity of the outputs they can produce in a given time. However, they also report that there is significant criticism on the accuracy and validity of this method.

Protocol analysis (PA) is another method for this assessment, which approaches the involved cognitive process more generally, without a focus on creativity [22,23]. PA involves recording different tasks, gestures and (think-aloud) thoughts of the creators. They are converted into a code system that is a qualitative categorization of the thoughts and actions which are then quantitatively analyzed based on when and how frequently they are performed. This method can be enhanced by techniques such as linkography to better understand and visualize the relationships between different elements in the process, which capture distinct content and structural properties of a creative cognitive process [2,24].

PA's strength is the meticulous categorization of different tasks and thoughts during the creative process. However, it is time-consuming for the researchers, and thus the participant sample size may not be large enough to capture the diversity of the process and to allow generalization of the results.

For a creative person, the focus of the assessment is usually on finding what personal traits correlate with the person's creativity [6]. To identify these traits, researchers may rely on self-reports by people in questionnaires or interviews. This method is reliable and easy to conduct, in the sense that it captures certain dimensions about a creative person. However, it falls short in considering non-personal traits as well as potential biases towards or by the interviewed person.

Methods to assessing the press depend on the context, which range from the whole of the society to organizational dynamics in the workplace and the learning settings, to name a few.

3.2.2. Assessing the Three Levels of Computational Creativity

Assessing computational creativity is commonly represented by evaluating the creativity of the outputs. In this regard, there is not much difference between the methodologies of assessing human and computer creativity. CAT with its panel of judges is the main means of this assessment. However, an alternative product assessment method is to use software to automatically detect creative qualities such as novelty and value. This is, at present, more experimental than practical, and is more useful for evaluating the creativity of automated outputs. For example, the software can measure the difference between the product and cases in the creators' knowledge base to evaluate novelty. This makes it a suitable method for assessing P-creativity.

Computational creative processes usually revolve on a linear or cyclic series of generation and evaluation tasks. Both generation and evaluation, despite being process-oriented, are often assessed through their products. Hence, the main ground for the assessment of the process would be the linkage and correlation between the product and process. Colton et al. [25], for example, developed FACE, a task-code system not very dissimilar from PA. The acronymous system contains coding for four tasks/criteria (framing information, aesthetics, concept, and expression) that can be used to assess the creative process by the computer agent.

The press and person in computational creativity has not been as thoroughly researched as the process and product. It is, after all, difficult to assume personality traits and society settings for AI. In her review, Jordanous' method to assessing press in CC is more between a computer and its human audience [8]. In this regard, IDEA is another code-based model by the developers of FACE which iteratively adjusts the creative performance of the computer agent based on the reactions it receives from the audience [25].

Assessing creativity in HC^3 and CST does not inherently differ from those for CC and creativity in general. In its original sense as computer co-creator, the computer agent's creativity is the same as in CC (Section 3.2.2), and therefore it is often approached in the same way. Otherwise, when the computer would be more a generative or supportive tool as in CST, the assessment would focus on the human's creativity as introduced in Section 3.2.1. In this case, the main themes of research are on the interaction between computer and human or between humans using the computer, and how these interactions affect the creative output. The interactions can be studied similarly to the usage of non-computational tools, for example, with PA.

4. Computational Creativity and Built Environment Design

The discipline of the built environment (BE) (architecture, landscape architecture, urban design, etc.) has long used computational tools to improve the designing experience. Creativity as an essential quality in this discipline has also been a focus of research on digital tools and media. However, to critically understand how such tools are used in BE design, and how they contribute to creativity, it is first necessary to understand how designers think and conduct design. Design thinking does not have a single widely accepted definition [2], however, many studies of design thinking identify and articulate design focusing on different mental activities and stages of designing, usually within an iterative design process [26]. For example, Brown [27] considers three stages of inspiration, ideation, and implementation within a thought process, emphasizing both divergent and convergent thinking, and both the synthesis and analysis of ideas for creative problem-solving. In essence, design thinking, as a set of mental activities for creative problem-solving, share mostly notions of the creative process amongst the Four Ps. On the other hand, components such as the background of people, ways of communicating ideas, and interactions among stakeholders, peers, and the market [27] are represented by the remaining Ps.

In this regard, presenting a holist picture of design thinking in the BE discipline, Lee, Ostwald and Gu [2] identify several components of design thinking under three broad aspects of creativity, collaboration and culture (hereafter, referred as the Three Cs), and discuss the role of computation in each topic, supported by case studies and formal research methods. In summary, their approach to creativity involves the processes in design with which products are generated, especially through interaction with generative algorithms. For the sake of categorization, this approach is rather direct and individualist, where the computational part was only used by one designer to directly participate in creative generation (i.e., using parametric design in various of their case studies). Collaboration pertains to the use of media and mechanisms through which team members communicate design ideas. Here, the team members have the opportunity to share and interact with the individual tasks as explained earlier. Finally, culture contains cognitive and linguistic particulars and differences between individual designers, which influence their design

approaches. The cultural diversity of designers offers different viewpoints and methods to approaching design problems, qualities with potential positive influence on creativity.

In this paper, the key components of creativity and design thinking are represented by the Four Ps and Three Cs, respectively, which are examined together to identify potential implications for the different levels of computational creativity (CC, HC^3 and CST) in BE design:

- Creativity: the notion of creativity in the Three Cs involves individualist cognitive processes leading to the creative product. The computer's first contribution to creativity is in the synthesis and analysis of the product, supporting the novelty and value aspects of creativity, in both its generic definition and as the first C. However, the nature of the computer's involvement depends on its role in the process. The use of computers assumes synthetical and analytical roles within the design process. On the CC level, the computer also controls the problem finding or initiation stages, because it actively takes part in design problem solving. Hence the process, with its individualist aspect, involves the internal "thought" processes of the computer agent as well. On the other hand, on the HC^3 and CST levels, this process includes a significant amount of human–computer interaction (HCI). The HCI aspect of the design process can itself be a creative output of the computer software, as the new processes and the new types of design-related tasks and flows emerge.
- Culture: this is the "human" side of the creativity. The person and their associated possesses together with HCI are influenced by certain culture. Given the cultural differences between people, the computer interface may require appropriate customization to enhance creativity. This customization, if done by the software in an autonomous fashion, would be another relevant area for the computer's creative involvement in BE design.
- Collaboration: in addition to the above-mentioned interactions between humans and computers, there are also interactions and communications between humans (and possibly between computer "colleagues"). Regardless of the level of inputs by group members, or the nature of their collaboration (the goal is unique and common amongst the team) or cooperation (with shared and multiple objectives across the team), creative methods of communication between members are another area for deepening the research on computational creativity.

In summary, as listed in Table 3 and illustrated in Figure 2, the Three Cs and Four Ps are represented by different design activities when computational creativity is involved. The first C (creativity), and partially the product and process are manifested within synthesis (generation) and analysis. The person and hence their inherited culture, and a part of the process, are also a subject to interfacing between human and computer. Finally, the press by harboring culture and collaboration influences the communication using computers. In the next subsections, these four design activities, namely, synthesis, analysis, interfacing, and communication are discussed. For each activity, to avoid confusion, a distinction is made between when the activity's title is itself the creative product and when it is the context where creative design output is produced.

Table 3. Different design activities and their relationships with the Four Ps, Three Cs, and key categorizations of computational creativity.

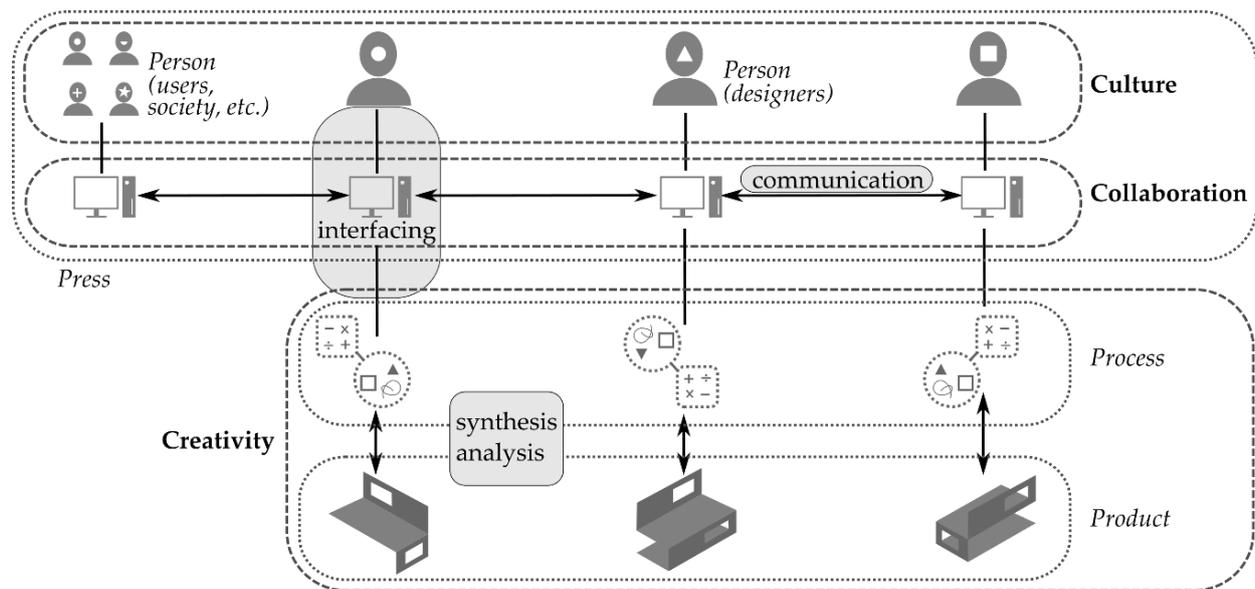| Design Activities	Four Ps [8]	Three Cs [2]	Relevant Roles and Categories [7,9,11]
Synthesis (Generation)	Product, Process	Creativity	Generate, Modelling, Colleague
Analysis	Product, Process	Creativity	Analyze, Book-keeping Find Problems
Interfacing	Process, Person	Culture	Support, Control Initiative, Communication
Communication	Press	Collaboration, Culture	Communication

Figure 2. The relationships between the Four Ps (person, process, product and press), the Three Cs (creativity, culture and collaboration) and the four design activities (synthesis, analysis, interfacing and communication) in facilitating computational creativity.

4.1. Synthesis and Analysis

Creative synthesis (generation) by computers differs from creative synthesis (generation) using computers. The former, as creative systems, is one of the central topics of AI [9]. These systems are intended to either behave creatively like humans or produce comparable results. This means that they should be capable of problem solving in the respective domain. In design, its problem solving includes a cycle of analyzing the problem and generating creative solutions. While there have been interesting developments in various creative art disciplines such as poetry [28], painting [29] and music [30], there has not yet been a comparable success in BE design.

On the other hand, there have been various computational systems which are regarded as partially creative by assisting generative tasks. Generative design algorithms are frequently used in BE design [31,32], even though they usually only generate without possessing the ability to learn and analyze the relevant knowledge and the generated products. As a result, its products are usually guaranteed to be diverse, but not necessarily novel and useful, especially when addressing a complex design problem. If such a system has an embedded evaluative component or communicates with an evaluative agent (human or computer), then their combination would fulfil the base criteria of being "fully" creative. Depending on the level of human involvement, the system can be either an example of CC or HC^3.

Assessing creativity (of the product) in such systems varies depending on the goals and motivations for the assessment. A common motivation is to evaluate the success of the generative process in producing creative outputs. As explained in Section 3.2.1, human judges are recruited to provide scores based on a given rubric when adopting CAT. For example, in a case study by Lee, Ostwald and Gu [2], four participants from architectural disciplines used parametric design to explore design alternatives for the conceptual design of a high-rise building with a maximum 2500 m^2 floor area. The jury panel of seven experts evaluated creativity of the generated designs of each participant by scoring them in four criteria: novelty, usefulness, complexity, and aesthetics. A similar application of CAT further suggests the criteria of technical feasibility and financial viability as indicators of creative appropriateness for a more environmentally friendly construction [33].

Another motivation is to study the interaction between the computer and the human users within the design process. The goal in this approach can be to understand what, when, why, and how computer is used by the human designer. In the above parametric design case study, and other related research [34–36], designers' interactions with the parametric system were encoded and visualized using PA and linkography to understand the types and patterns of interactions between the designer and parametric design. By correlating with creativity assessment of the product, we can isolate and reveal those interactions and patterns that can enhance creativity.

The current trend in researching computational creativity, synthesis and analysis in BE also revolves around studying the broader human use of computational tools beyond professional designers, especially using parametric platforms. Given this interest, we may see further extensions of this trend such as participatory parametric design [37,38].

4.2. Interfacing

The interface refers to "the software and input devices by means of which a computer and its (human) user communicate" [39]. As explained earlier, this communication or interaction can influence the design process and creativity while itself also being influenced by the human designer. Creativity in terms of interfacing may refer to two different ideas. One idea involves a "creative" interface, which automatically offers new ways of interaction between human and computer. The other is to view the user interface as a CST, a medium to enhance the user's creativity.

A user interface (UI) that changes its behavior to suit its users is called an adaptive UI [40]. Many existing computational tools, including advanced CAD and building information modelling (BIM), try to understand and memorize usage patterns and suggest them back to the users when a similar context occurs in the future. However, the question is whether or to what extent such capabilities of being "adaptive" equal being "creative". A challenge in answering this question is that the concept of computational creativity is not usually applied to outputs outside common artistic and design domains without tangible products. Meanwhile, the issues associated with an interface usually contain relations, behaviors, gestures or eye movements, etc. After all, how much do adaptivity and creativity differ from each other? Linkola et al. [41] argue that self-adaptive systems are inherently creative because their adaptations are unique and useful because of the unique situation to which they react. Does this uniqueness and usefulness suffice for adequate levels of creative recognition, despite the apparent absence of surprise? This is an open research question.

In the literature, adaptive UIs is more a topic of machine learning rather than CC. Among the target audience of adaptive UIs are people requiring educational [42–44] or disability supports [45,46], not necessarily creators or designers. This makes it difficult to review adaptive UIs' influence on CC and HC[3] or even productivity in design disciplines. Studies on both adaptive UIs and creative, artistic, or design tasks are scarce. In one example, an experiment [47] on an adaptive UI for filmmaking provides a method for the software to adapt based on users' satisfaction and the time spent on different tasks by users of different proficiency. The software changes its complexity based on the user's feedback, and therefore created a more efficient interface to suit different levels of proficiency.

As a CST, a design UI's main role is to facilitate effective communication between users and the software. One of the earliest capabilities of design UIs was to parameterize the human input [48]. While the common parameterization functions have been based on raw geometric definitions (such as selecting two points for creating a line) there are more complex functions in newer software. A particularly relevant ability in some CAD tools is to convert lower-level descriptions to complex design, a quintessential feature of parametric design. More advanced parameterization involves interpreting the designer's natural language such as human gestures and behaviors. For example, Cheon et al. [49] created 3D parametric geometries from 2D sketches, and Davis [50] explored augmented reality (AR) to translate hand gestures into design commands.

The main methodologies of studying CST interfaces are similar to those of generative tools. They may be studied to see if their usage contributes to creative outputs [1]. Some examples are comparisons between CAD and manual design methods [51–55], between virtual and real representations [56] or between different digital platforms or environments (e.g., desktop, virtual reality (VR), AR, etc.) [57,58]. Alternatively, other research has used PA to understand the designer's interaction with CSTs [59,60].

These examples suggest that the present interest of computational creativity research in BE design are rather technology-oriented, which focuses on exploring the potential usefulness of emerging hardware and software technologies for interpreting human design actions or representing interactive visualization of the design process and product. More intelligent UIs such as adaptive design interfaces are not yet a focus of the field. It is not clear whether this is because of a lack of interest and needs from the sector, or due to the disciplinary distance between AI and BE design. Nevertheless, this lack of development in intelligent UIs presents future opportunities for computational creativity research.

4.3. Communication

Creative communication is a broad term for the use of communicative methods to connect with the audience and significantly influence them [61]. A computationally creative communication is hence when such a method is automated. There are numerous studies on the broad concept of creative communication in social sciences and education [62,63], healthcare [64,65], and business [66,67], but is rarely approached by BE and design researchers [68], even on collaborative design where communication matters the most. This issue may be rooted in an essential purpose of creative communication as to impress or engage the audience. However, collaborative design research traditionally concerns communication between designers and not clients or end users. This is why most relevant examples in the literature pertain to when the audience (or end users) are also the designers through participatory design or co-design; co-creation, for example, in participatory urban projects [69–71] or heritage database developments [72].

Computational marketing of products is an emerging research topic across IT and AI disciplines [73–75]. The marketing involves big data analysis and profiling of existing and potential customers, and automating adverts or generating feedback accordingly. Although the creative-vs-adaptive debate is also applicable here, the main issue seems to be a fundamental difference between the definitions of products in marketing and BE design. Consumer products are usually mass-produced and mass-distributed, leaving room for a statistical analysis to roll out computationally applicable marketing strategies, and in return to influence the designer's next creative moves. On the other hand, BE design solutions are usually unique and target individual clients. A comparable topic in BE research is marketing for housing projects. Despite some studies on this particular topic (such as [76,77]), our search could find little that explicitly traces the marketing or end-user feedback to its effect on subsequent architectural design. Such a feedback loop would be necessary if a computational marketing strategy is adopted to enhance creativity.

Nevertheless, there are automated procedures for supporting market-based decisions in BE disciplines. An example is a proposed decision-support system which guides the designer to select materials based on the performance of their suppliers [78]. This system is akin to a generative/evaluative system which coordinates with the designer, and hence, can fall under HC^3. A different example of an HC^3 attempt is an algorithm devised to find 3D BIM viewpoints for more efficient facility management [79], a point of communication between different stakeholders in design and management. Similarly, one can argue that building automation, or "smart buildings", or in general, the automated adaptation of selected building functions based on human interactions can have elements of a creative communication [41]. They are UIs which indirectly or retrospectively connect designers with the end users. Although such topics are rarely concerned with creativity in an explicit fashion, there may be merits in such automation contributing to collaborative decision making.

Moving on to the next level, there is more progress in literature on CSTs for communication than CC and HC^3. These support tools are different from those interfaces explained earlier. The former were UIs which allowed a person to interact with the software. The CSTs for communication are still UIs, but they also facilitate communication between designers. Given their nature as UIs, research methodologies to examine creativity are similar to those discussed in the previous sections, i.e., CAT for assessing product creativity, and PA for process, behavior or cognition related studies. As for the former, the assessment usually compares the creativity of outputs with and without digital communication in a collaborative design context, or between different digital tools. Currently, some main research foci are the use of VR, AR, and mixed reality (MR) for communication. For example, Chulvi et al. [80] conducted a case study with four teams of industrial design students, two of whom used a virtual environment capable of sketching while the other two interacted face-to-face. The study found a slight decrease in creativity when using the virtual communication. In contrast, in another case study for architectural design [81] significant increases in the creativity scores were observed when using a multi-user virtual environment compared to using sketches.

Similarly, it is equally useful to apply PA for studying digital communication. A major advantage with using this method (comparing to the previous cases involving individual designers) is that here conversations between team members can naturally occur, which can better facilitate the "think-aloud" aspect of their thoughts [82]. This allows understanding of the dynamics between different team members in addition to the tasks performed by each individual. Using PA for analyzing the role of digital media in collaborative design dates back to over two decades' ago [82], leading to the understanding that different types of digital collaborative environments can affect design process differently [83]. However, there has apparently been a gap in studies across the topics of creativity and collaborative design environments. There are several studies which focus on digital media and collaborative design, for example, examining the potentials of new collaborative interfaces such as tangible user interface (TUI) [84], stationary AR [85,86], mobile AR [87], and VR [88] using PA. There are also studies on collaborative design and related creativity concepts [89–91] although without a computational focus. However, computational and cross-topical studies are scarce. An only example from our search is Chowdury's study [70], where PA was used to analyze six design tasks devised in an participatory urban design project via virtual media, and then the results were assessed by an expert panel.

Using PA in studying collaborative design would also shed light on personal differences between the group members. In a cross-national comparison between Swedish and Australian architects using parametric design, Lee, Ostwald and Gu [2] found differences in their individual creative behaviors. They argued that in a collaborative project, such differences may complement each other and contribute to an overall more creative process.

Similar to the research trajectory for interfacing, an emphasis of computational creativity literature in terms of communication involves the potentials of the new technologies and digital media. In addition, there is also a strain of research interested in the software aspect of communication, especially regarding the users' interaction with products, i.e., buildings, which has shown positive impact on informed decision making and marketing potentials.

5. Discussion

This paper presented a critical review of defining and assessing computational creativity in built environment (BE) design. The study has discussed three levels of computational creativity, including computational creativity proper (CC), human–computer (co-)creativity (HC^3), and creativity support tools (CST), and identified four design activities where these levels can be utilized, including synthesis (generation), analysis, interfacing, and communication.

The study has found that in some of the activity-level combinations not only are there gaps in the current literature, but in some cases the entire research area is not defined. This is especially notable in applying the levels of CC and HC^3 on interfacing and communica-

tion in BE design. This lack of research and understandings may have different reasons. A historical reason is that both areas (interfacing and communication) were somehow neglected until more recently, with the developments in HCI and design collaboration. Secondly, the concept of creativity has usually been associated with traditional art and design products, whereas computer interfaces and communications have also not been associated until more recently. Hence, it is even more challenging to define and contextualize them in BE design, especially because designing them pertains to other disciplines such as interaction design. The lack of clarity in definitions may have delayed their departure from traditional research areas in the field, to be further studied in their own right.

On the other hand, there is considerable research on CSTs for all activities, with the research usually involving understanding the influence of these tools on the creative output by the designer. The studies usually differ from each other according to the examined CST, rather than the methodologies of the studies; CAT has predominantly been used for assessing products or PA for assessing processes or the designer's behaviors. In this regard, the research interest and trend in CST seems to continuously evolve, influenced by the latest developments in computational design technologies, while the research methodologies remain largely unchanged. Although methodological innovation is important for the vitality of the field in the longer term, having consistent research methods and techniques will allow designers and researchers to critically compare and benchmark computational creativity especially with new and emerging CSTs.

In conclusion, while it is important for the research on computational creativity in BE design to continue to consider the development and effect of new computational design technologies, future research should be planned to fill the current gaps pacing towards further studying the interaction and communication between designers, and more importantly between the designer and the computer. Following the frameworks (Tables 2 and 3 and Figures 1 and 2) as presented in this paper, computational creativity research can be developed in a more integrated and balanced manner to further advance and innovate BE design.

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