INTRODUCTION: DESIGN ARTEFACTS AND CAAD TOOLS
Latest research on tools and media to aid architectural design stresses the need to instrumentalise dialogs between both digital and physical representations of design information, such as the development of collaborative mixed reality applications (Billinghurst and Kato, 2002) and tangible user interfaces for design (Ishii, 2008). On the professional domain, current digitally-mediated practices already deal with this interaction on a regular basis under stipulative definitions such as “digital tectonics” or “digital manufacturing”. Notwithstanding the evident semantic oxymoron, these concepts are usually described as ‘technology toolkits’ rather than socio-technical instruments for design with a complex structure and diverse dimensions to be considered, such as its functional, structural or temporal features (Rabardel and Bourmaud, 2003). This emerging complexity has already pushed forward a reflective analysis on the role of models and representations in design from different perspectives such as human cognition, human-computer interaction or design education. In this context the inquiry raised by Frazer (2006) tries to refocus the discussion on the actual role of tools from a developmental perspective: “What is it about computer-aided design that needs to be aided?” This question brings foreground the imperative corollaries of understanding how design works and how can we describe this complex eco-system (Gibson et al, 2008) of distributed relationships.
Models, from a design perspective, are understood as representations of a set of design information for a specific purpose. Previous research on architectural modelling and representation has often been reported from an operational and static perspective; however, detailed analyses of the interactions between representations and their role as mediators between the designer and the designed outcome have been hardly scrutinized. We argue that in the context of current digitally-mediated architectural practices, models are a way to craft the interaction between the designer and the environment as a socio-technical instrument in a complex, distributed network among media, people, disciplines and tools, facilitating the creation of new design knowledge (Tzoukas, 2009) and the emergence of organizational and creative practices (Kocaturk, 2007). From this perspective, the understanding of the implications of both physical and digital modelling techniques on these mediating and societal processes is a matter of utmost concern. This understanding does not only defines new production alternatives but also contributes to the definition the representational and symbolic role of models (Vera and Simon, 1993) and their impact on the design media, organizational and usage schemes (Rabardel and Bourmaud, 2003) and new emergent design instruments and innovations (Desouza et al, 2007; Lyon, 2008).

The evolutionary dialogs between both digital and physical models have certain ‘pros and cons’ for the design process: virtual models are usually clusters of information which aim to define a very precise geometry and building information based on discrete but interrelated components, and can be easily explored and modified. On the other hand, physical representations are useful for the evaluation of physical variables such as gravity and direct manipulation, client reviews, material properties and tectonics, or exploration of constructive processes and methods. Nowadays, the use of a variety of virtual models for design explorations and the fabrication of physical prototypes are becoming commonplace and have had an impact both in the definition and organization of the architectural practice (Klinger and Vermillion, 2005). However, during the digital fabrication of physical models there is, unavoidably, a loss of design information and a huge simplification of the complexity that rules the relationships between the components of the digital counterpart, as only a limited amount of design solutions can be represented at a time in accordance with the availability of the crafting or machinery capabilities. Despite this, inter-relationships between both techniques have evolved to continuous feedbacks between both digital and physical techniques, allowing the emergence of hybrid modelling schemes such as “physical models of digital materials” (Oxman, 2007).

In this paper, we introduce a novel understanding of the relationships between physical and digital production methods in the context of model-making in architectural design. This framework results in the construction of four core conceptual categories that describe those dialogical relationships: directed production, undirected production, dual models and mixed models. In the next section, a framework for this purpose is presented, as well as an updated set of concepts on the fabrication and manipulation of technology artefacts in the context of architectural design and human-computer interaction. The conceptual categories, together with some case studies and their core characteristics are presented in the third section of this paper, prior to the final conclusive discussion.

**GROUNDING A FRAMEWORK**

**New digital practices**

Klaasen (2002) states that the model is a representation of a conscious simplification of reality, filtered and determined by cultural and individual backgrounds which necessarily conceives a systematic understanding of the reality and a set of reductional constraints (Figure 1). This context-dependant definition is aligned with the current rise of the new digitally-mediated architectural profession, since a constructivist approach to design based on the definition of a distributed system is the background for the new computer-supported practices.
The distributed nature of the design activity, as well as the new digitally-mediated and multidisciplinary practices, requires an updated understanding of the role of tools and technologies in our discipline. The first definition of models on the specific knowledge domain of digital design was proposed by Mitchell (1975), who proposed three categories: iconic models, symbolic models and analogue models (Figure 2). Mitchell’s proposal is mostly focused on two dimensions: the construction of the model and its knowledge retrieval scheme, however it must be framed within the first rise of computational capabilities related to the architectural practice: microprocessors and the recent completion of Sydney’s Opera House by John Utzon and ARUP opened in 1973 -after well known controversies-, later followed on the 1980s by exemplary buildings on the field of CAAD such as The Menil Collection (Renzo Piano, Houston, 1982-1986) or the Schumberger Research Center (Anthony Hunt, Cambridge, 1982-1985). Architectural modelling is deeply rooted within the availability of technologies at some specific period and which ideas were being expressed through those models following the local and temporal \textit{Zeitgeist}. Nowadays, under the influence of emergent digitally-mediated practices, a higher specialization is demanded by the industry and the modelling requirements ask for additional collaboration such as in-house modelling groups or external support such as BIM trainers or visualization offices’ consultancy.

\textbf{Modelling tools: From artefacts to instruments}

Rabardel and Bourmaud (2003) present a framework to define and/or identify technology artefacts and instruments on the context of human-computer interaction. Their ontological approach entails the potential conversion, under certain conditions, from an artefact to an instrument. An artefact becomes an instrument by identifying usage schemes originated by its use and hence, by establishing a socio-technical system between the model and the designer. They (Rabardel and Bourmaud, 2003) postulate that mediational processes that construct those systemic interactions can be described from three perspectives: structural, functional and temporal:

- \textit{Structural features} of an instrument entail the set of both logical and physical components
of the socio-technical system and allow the engagement of the technological counterpart within a usage scheme.

- **Functional features** are described as the different mediational roles of an instrument: mediations aiming to know the object (knowledge that can be retrieved from the model itself), and mediations aiming to concern action on the object (knowledge that can be retrieved from manipulating the model).

- **Temporal features** are described as “instrumental geneses”. The concept of instrumental geneses defines appropriateness and culture-based mediational means as a way to both discover how an artefact emerges within a usage scheme and also to identify its evolutionary characteristics that might lead to user-led innovations and emergent properties (Desouza et al, 2007).

**Virtual-physical modelling tools: Digital fabrication and mixed reality**

In the digital era (Kolarevic, 2004), the relationship between physical and virtual representations has been understood as an asynchronous sequence. The computer-aided production of the physical representations is usually prepared once the virtual model has reached certain level of detail, and it is used as a checking or representational instance during the last stages of the design process, or as a exploratory model to verify the behavior of specific design variables, such as structural behavior or lighting, among others. This sequential relationship has been developed and improved by the use of reverse engineering techniques. In this case, scanning and surveying technologies are used in order to add real-world information to a virtual model during the design process, mostly for simulation purposes. This real-world information is not only based on the physical geometry, but also on physical properties such as gravity. In this case, design is understood as a continuous iterative process between both virtual and physical realms. This iterative description of design was made by Schon on his “reflection in action” schema (Schon, 1983) and nowadays has been supported by the use of increasingly accurate scanning and photogrammetric technologies.

A further development on the relation between physical and digital representations is ‘mixed reality’ (MR). It is a concept that explains the intermediate instances between the purely real and the purely virtual realms within a ‘virtuality continuum’ (Milgram and Kishino, 1994). MR has been developed during the last two decades and has been largely used for entertainment purposes, although is already considered a quite promising technology in terms of communication and collaboration during the design process (Billinghurst and Kato, 2002). So far, in architectural design MR systems have been understood mostly as a visualization aid, by providing a method to visualize architectural information by adding human interaction within different intermediate levels of the reality-virtuality continuum: augmented reality (AR) consists of the incorporation of virtual infor-
mation within a real environment, such as photomontages and webcam-based 3D visualization and tracking. On the other hand augmented virtuality (AV) incorporates “real-world” information within a virtual environment, e.g. in immersive systems.

‘Interreality systems’ is a new concept within mixed reality derived from Gintautas and Hubler’s (2007) research in the subject-field of Physics. This concept conceives the existence of two different stages of the relationship between the digital model and its physical counterpart within any mixed reality system. A first -and more primitive- stage can be defined as ‘dual reality’ where both realms are visualized but not necessarily related; and a second and more elaborated stage called ‘mixed reality’, consisting of a coupling between both realms in a coordinated, synchronic and bidirectional way.

**DIALOGS BETWEEN PHYSICAL AND DIGITAL MODELLING METHODS**

Our proposal allows to describe the relationship between digital and physical models by proposing four different categories, based on the temporal analysis of the flow-work and roles of both digital and physical instances within the modelling process: 1. Directed production, 2. Undirected production, 3. Dual models, and 4. Mixed models.

**Directed production**

In this category, the relationship between digital and physical representations is understood as a sequence on which a virtual model is crafted and then a physical representation is produced from it, on a dependant and asynchronous sequence directed toward the production of the physical model. The manufac-

*Figure 3*

Final presentation model built by using a computer-controlled milling machine; example of directed production. Photo: A. Veliz.
turing of a physical representation demands a previously finished virtual counterpart, and its fabrication entails a significant loss of information. It is usually referred to as an exploratory method to verify the behavior of specific/isolated design variables, such as massing models, or as a final presentation model (Figure 3). In this case, instrumentation occurs by retrieving knowledge from the model.

**Undirected production**
In the category of undirected production, the production of a physical model is not the goal-state, but part of the modelling continuous process. It can be defined as a *loop of continuous and asynchronic iterative feedbacks between physical and digital representations*. This scheme has been facilitated by the use of reverse engineering techniques; scanning and surveying technologies are used to add real-world and physical phenomena information to a virtual model during the design process, mostly for simulation purposes. Therefore, knowledge is retrieved both from the model, as well as from its examination and analysis.

An example of undirected production is the modelling process that supported the design of the dome of Louvre Abu Dhabi (Arch. Jean Nouvel). On the report published by Koren (2011) he describes the construction of the physical model of the structure and cladding of the dome. Differently from the “directed production” scheme, the construction of the physical representation, in this case, is not the goal-state of the modelling process but a stage on a more comprehensive and continuous flow of feedbacks between physical and digital modelling techniques. The analysis and knowledge retrieval was focused on the analysis of the lighting conditions, structural behavior under harsh environmental conditions, and cladding and prefabrication constraints. In order to complement the physical model, virtual modelling feedback was also utilized. Lighting conditions were analyzed and reported by Tourre and Miguet (2010) and structural design and cladding conditions was published by Fisher and Craig (2011).

**Dual reality models**
Dual reality models are referred to a subset of mixed reality models. Following the conceptual definition of “interreality systems” provided by Gintautas and Hubler (2007), dual reality models are entities on which the digital model and its physical counterpart do not provide a synchronic and correlated dialog, hence is mostly used for visualization purposes rather than design instruments (Figure 4). Illustrations for this kind of system are *post-facto* made photomontages of an architectural project and immersive mixed reality videos (Figure 4). Developing and report of dual systems do not entail necessarily an appropriateness strategy, hence the functional dimension of the model is not elicited.

**Mixed models**
The main feature of mixed models is stated by Gintautas and Hubler (2007): the change of phase from a dual reality model and a mixed model leads the way to the *discovery of emergent properties within an interreality system based on a synchronic and bidirectional feedback between the digital and the physical counterpart*.

Our ongoing work attempts to discover a definition of “interreality systems” on the subject-field of architectural design and its applicability; one of the case studies selected for this research is the Hybrid Ideation Space (HIS) reported in (Dorta, 2007; Dorta, 2008). The Hybrid Ideation Space is an immersive system to augment sketching and model-making activities within a design course at the University of Montreal, Canada. The system promotes a *direct and reflective dialog with the design representation*. The analysis of this instrument is highly focused on the design process and the flow of design information and knowledge among different representations. Design information is retrieved, represented and manipulated by using both analog tools and computer-based systems. In order to assess the system in comparison with traditional design tools, the methodology reported in (Dorta, 2011) makes use of a group of Industrial Design students and the cognitive aspects of the HIS as an interface was evaluated.
using NASA Task Load Index (TLX) which provides a workload score based both on cognitive aspects of the demands imposed to the subject (mental, temporal and physical demands) as well as the interactions between the subject and the interface (performance, effort and frustration). Final results of the assessment report show that students formulated design ideas more easily based on factors such as time spent, concept production and success rate. Also a direct relationship was observed between students’ motivation during the use of the tool and their collaborative practices during the use of HIS.

**DISCUSSION**

Despite the lack of agreement on a descriptive model for design, the understanding of different context-based relationships is of fundamental importance to continue developing knowledge and tools to actually aid the design processes. Interreality systems and their use in architectural design context are a developing research field in the Mediated Intelligence Research Group in the University of Salford. This paper specifically focuses on the ongoing PhD research of the first author.

We have presented and summarized a framework to name and define different dialogical relationships between physical and digital modelling methods, as well as presented some case studies to illustrate them. The perspective of this study is to formulate a conceptual framework to ground further research on design tools, technology development and human-computer interaction in design. For this purpose, this study only partially described the socio-technical system that constructs the set of relationships between the designer(s) and the designed object. Referring to the description of Rabardel and Bourmaud (2003), instruments configure not just levels of usage and usage schemes, but also “activity families, classes of situations and domains of activities”. On socio-technical systems, evolutionary behavior and emergent features are often unanticipated and their description might entail rather a
presumptive than descriptive perspective, however its analysis is also required in order to elicit unexpected usage innovations and modifications (Desouza et al, 2007).

In the experimental design of Gintautas and Hubler (2007), the correlation between the real and the virtual model was evident at the moment of measuring the oscillations of a real pendulum and its virtual counterpart. Despite this, potential beneficial characteristics of an interreality system as a design tool cannot be defined and therefore measured on a fully quantitative basis. Even if the original research (Gintautas and Hubler, 2007) on this matter states that there is still no available technology to instrumentalize this -still- theoretical concept, its usefulness and applicability has been already explored within the fields of robotics, psychology, e-learning and e-health studies (for example Robert et al, 2011; Edelman, 2010; Riva et al 2010). Hence, our study is conducted to propose not just a conceptual framework to depict the applicability of interreality systems on design from a cognitive perspective, but also to propose a set of instrumentalisation guidelines for future technology development. It is anticipated that this new approach to develop mixed systems will contribute to a new set of cognitive instruments for design.

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REFERENCES


