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Three Categories of Design Thinking: Routine, Simple/Complicated and Complex

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Abstract

Design thinking consists of a wide range of methods and a key issue for design research and practice is to identify which kinds of design thinking methods are appropriate for different design situations. This paper offers a new, coherent and well-defined approach dividing Design Thinking methods into three exclusive categories each specific to one of three non-overlapping types of design situation: Routine, Complicated and Complex. This exclusive categorisation of design thinking methods on the basis of defined categories of design situation makes it possible to quickly identify appropriate design processes, organisational needs and resources for any design project. The paper introduces several new foundational concepts in design theory and associated new paths of design research. Particularly, the paper introduces prediction of outcomes as an essential and central role aspect of all design , creativity and art. The paper concludes by pointing to the emergence of a fourth category of design thinking that will require redefinition of Design Thinking as a concept.

Keywords

Design Theory, Design Research, Design Practice, Prediction, Outcomes.

Introduction

What is *design thinking*? Human design activity always occurs in mind in some manner and this idea that design is essentially a thinking process is evident in the extensive design research literatures from the 1950s to the present relating to design cognition, design methods and creativity across hundreds of design fields — see, for example Ackoff, 1974; Akin, 1979; Al'tshuller, 1984; Alexander et al., 1968; Altman, 1974; Amabile, 1983; Archer, 1965; 1968; 1984; Bazjanac, 1974; Brotchie, 1974; Cross et al., 1981; Daley, 1982; Darke, 1979; Eastman, 1968; Eder, 1966; Fielden, 1963; Forrester, 1971; French, 1971; Glegg, 1969; 1971; Gregory, 1966; Gregory,1966; Jones, 1966; 1970; Jones & Thornley, 1963; Lawson, 1980; Leech, 1972; Lera, 1981; Levin, 1966; Lewis, 1981; Matchett, 1963; 1967; Matousek, 1963; Middendorf, 1969; Montgomery, 1970; Newell & Simon, 1972; Pahl, 2005; Pye, 1964; Rittel, 1971; Rittel & Webber, 1973; Roe et al., 1967; Ross, 1966; Simon, 1969; 1981; Spillers, 1974; Ullman, 2010; Woodson, 1966; Zwicky, 1969; Zwicky & Wilson, 1967—.

Over the last 50 years, authors of the above and similar texts on design research have identified many methods for improving design thinking, some comprising collections of methods such as Jones' (1970) early collection, *Design Methods: Seeds of Human Futures*. One of the challenges for the design research field is identifying which of the thousands of the *design thinking* methods is best suited to specific design situations. Addressing this challenge has been limited to date in part because of widespread confusion about the role of design theories and methods (Love, 2010) along with a widespread lack of clear definitions of concepts and well justified analysis along with ongoing confusion, conflation and confabulation in design theories and concepts in much of the design research literature — see, for, example, Eder, 1981; Love, 2000; Parnas & Clements, 1986; Pugh, 1990; Talukdar et al., 1988; Ullman, 1992—.

The focus of this paper is on design research analyses that separate the universe of design situations into four non-overlapping categories and define 3 distinct categories of design thinking methods (design methods) that map one to one onto 3 of the identified four categories of design situations. Because of the mess of definitions and analyses in the design literature identified previously this paper will first define and explain the theory concepts used in this paper. Additionally, this preliminary section will draw attention to the central and essential role of prediction in all aspects of design, creativity and art; the importance of the role of outcomes in understanding design thinking and of clearly differentiating outcomes of designs from outputs of design activity.

To recap, this paper develops criteria that define three categories of design thinking methods each applicable to a defined category design situation. The order of analysis in this paper is as follows;

1. A brief overview of the history of development of design thinking methods leading to the current Stanford/IDEO model of design thinking.

2. Definitions of design used in this paper.

3. Outline of the differences between design outcomes and outputs

4. A review of the important central and essential role of prediction of outcomes in design, creativity and art activities.

5. Definition of routine, complicated, complex and chaotic systems.

6. Outline of human biological limits of the ability to predict outcomes.

7. Identification of three categories of design thinking methods for: routine design; complicated design and complex design situations based on criteria that explicitly distinguish between them in terms of their limits to being able to predict outcomes resulting from design activity.

8. Description of design thinking methods for routine design situations.

9. Description of design thinking methods for complicated design situations.

10. Description of design thinking methods for complex design situations.

11. Implications for design outcomes, for design theory and for design practices.

12. The emergence of a fourth category of design thinking.

History of the Stanford/IDEO Design Thinking Model

Putting aside the issue of whether all the thousands of design methods are design thinking methods, the history is relatively clear for the design thinking method taught by Stanford university, many design schools, and used by IDEO and a wide variety of businesses.

The concept of design thinking and the first use of the term emerged from the engineering design and creativity movements of the 1950s and 1960s. The first use of the term *design thinking* is typically attributed to Arnold's engineering design thinking developed in the period prior to 1959 at Stanford Engineering Department and published in lecture notes that emerged in 1959 as Arnold's book *Creative Engineering*. In parallel emerged a variety of different design thinking methods eventually evolved into the specific design thinking method taught at the Stanford university Hasso Plattner Institute of Design (d.school) and promoted by IDEO and others. Clancey (2017) in his relatively recent edited version of Arnold's Creative Engineering noted the term design thinking has evolved, and according to David Kelly, founder of the Stanford d.school and IDEO, the recent structure of Stanford's design thinking is in part based on the structure of McKim's visual thinking design methodology (Clancey, 2017).

Historically, there are parallel pathways of similar design thinking that emerged from the 1950s to the present across the world, especially in the sphere of the USSR, as an ongoing focus on thinking in design and more technically *design cognition* emerged as part of a drive to improved design output quality via systemization and automation in design activity. As for Arnold's design thinking that emerged first in engineering design, it was echoed later in architecture and planning and more recently taken up in Art-based design education fields. This progression can be clearly seen in historical review of tables of contents of key design research journals such as Design Studies, publications of the Design Methods group and the WDK group that later evolved into the Design Society.

Over the last decade, the Stanford/IDEO model of design thinking has become popular in business development, entrepreneurship and enterprise and is now widely taught as a design method in design schools worldwide — see, e.g., AANSW, 2013.; Dell'Era et al., 2020; Frisendal, 2012; Müller-Roterberg, 2018; Plattner et al., 2011; Plattner, 2010— and the recent literature on design thinking has primarily focused on categorising different ways of undertaking this Stanford/IDEO style of design thinking — e.g., Dell'Era et al., 2020; Müller-Roterberg, 2018—. It is widely considered to be well suited to, and form part of the pantheon of, human-centred design and participative design methods intended for the development of products and services by innovation driven and design driven companies and has been adopted especially in design education deriving from Art (Ambrose & Harris, 2010; Brown, 2008; Cohen, 2014; Greene, 2010; Higgins, 2020; Liu & Mannhardt, 2019; Lockwood, 2009; McKendrick, 2020; Meinel et al., 2011; Sato, 2010; Shamiyeh & DOM Research Laboratory, 2010).

This design thinking method taught at the Hasso Plattner Design Institute at Stanford is grounded in a combination of brainstorming about problem framing and design solutions and follows a six element design thinking process as shown in Figure 1 (Müller-Roterberg, 2018; Plattner et al., 2011; Plattner, 2010).

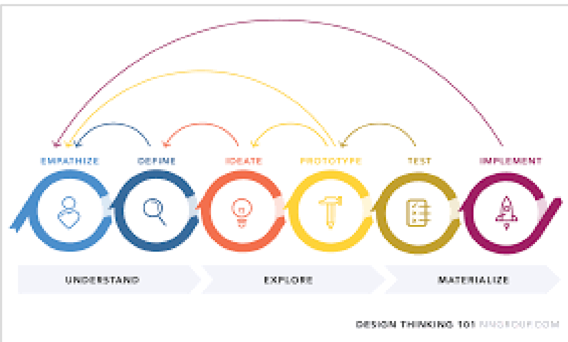

Figure 1: *Design Thinking process courtesy NNGROUP's Design Thinking 101 program (nngroup.com).*

Figure 2:*Design thinking using post-it notes.*

Teaching and using this design thinking process is typically implemented in participative design processes with information stored in short statements on post-it notes sorted using topic clustering and simplified bubble sort methods as illustrated in Figure 2.

In spite of the widespread enthusiasm for the Stanford/IDEO design thinking model, its take up by many large organisations and university design schools, and its current dominance as a design method, there are widely held criticisms — see, for example, Gerber, 2018; Hernández-Ramírez, 2018; Iskander, 2018; Lee, 2021; Loewe, 2019; Rodgers & Winton, 2010—.

In the main the criticisms centre on;

- Design Thinking (IDEO/Stanford/Art and Design) is a dumbed down version of what designers are trained to do.
- It focuses only on human centred design and user experience-based design, which are only a small part of the broad spectrum of design topics and disciplines.
- It is designed to be conservative and maintain the power of designers over all other stakeholders.
- Design thinking is primarily used to manipulate managers and sponsors into accepting and funding activities of commercial design studios.
- It produces sub-optimal solutions and focuses on a techne perspective.
- It is not suited to addressing organisational or design problems outside a user-based products view.
- The design thinking process is used to manipulate staff in organisations to accept changes proposed by management or projects approved of by management.
- It fails to address group dynamics issues.
- Overlooks lack of knowledge and expertise in participants that if remedied would result in better solutions.
- Lacks an ability to address highly complex design situations.
- There is more to the scope of designing than human factors and user experiences of products.
- Successful designing requires more training and expertise than available to the groups of participants doing the design thinking process.
- There is insufficient intelligent critique both of design thinking and within the design thinking activities.

In short, from a design research perspective, the Stanford/IDEO design thinking method can be perhaps better seen as just one of many topic-specific design methods that together provide the ecology of design thinking and design cognition methods across the hundreds of different design fields. From this perspective, a primary concern then becomes addressing the question, *Which of these design thinking methods are best suited to which kinds of design situation?*. Addressing this question is the primary purpose of this paper.

Definitions of Design

Before continuing, there is a need to define some basic terms relating to design. Across design fields there has been extensive confusion, lack of clarity and lack of agreement about definitions of *design* and related concepts in the design research literature — for, example, Eder, 1981; Love, 2000; Parnas & Clements, 1986; Pugh, 1990; Talukdar et al., 1988; Ullman, 1992—. Review of over 400 definitions of the terms *design* and *design process* (Love, 1998) identified widespread theoretical weakness of such definitions in the literature, often due to limitations from parochiality. Critical analysis of definitions of design led to the following definitions that avoid the identified weaknesses in other design definitions.

A *design* is a specification for making or doing something Or in plain English,
A *design* is a set of instructions how to make or do something, This then extends into:
Designing is the activity of creating designs, And
A *designer* is someone or something that creates designs, and in line with the above,
Design Theory is theory describing the creating of designs, and similarly,
Design research is research aimed at producing design theory.

In terms of adjectivally naming parts of disciplines, the term *design* is used to identify those parts of each discipline that are specifically concerned with the activity of design in that discipline and to distinguish that area from the more general knowledge in that discipline. For example, the term *engineering design* is used to distinguish the knowledge and skills of the discipline of engineering concerned with *design* activities as distinct from general engineering knowledge and skills independent of design such as stress analysis, kinematics, metrology etc. Similarly, the term *business process* design distinguishes the knowledge and skills for *designing* business processes from the knowledge and theories *about* business processes. Similar again, the term *graphic design* is used to distinguish the knowledge and skills of *designing* graphics from general knowledge and theories *about* graphics. The above definitions will be used and assumed in what follows unless otherwise stated.

Design Outputs and Design Outcomes

Design *outputs* and design *outcomes* are different. They are different concepts and have different roles, properties and purposes in design practice and design theory. To make useful and valid theory about design activity, it is important to distinguish between them when researching, theorising about and practicing design.

Design *outputs* are the immediate results of design activity, e.g., the drawings, computer files, specifications and the *designs* that are the specifications that define exactly which things and services are created and how they are created. Design *outcomes* are the *consequences* in the world from things and services created by using design *outputs*. Design *outputs* and design *outcomes* can be seen as different elements of a sequence in which design activity results in a design *output* that can be made into a *real-world product* (the actualised design) with *real world consequences* (the design *outcomes*) as shown in Figure 3 below.

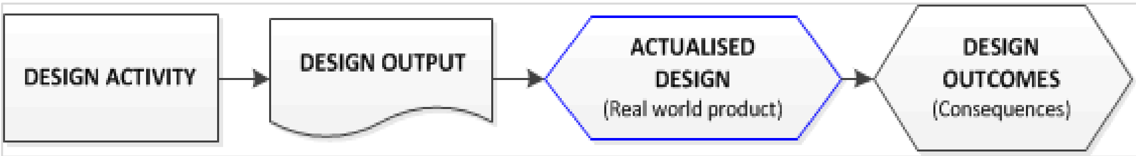

Figure 3: *Design activity results in real world consequences (design outcomes).*

It can be reasonably argued that design *outcomes* are a much more important focus for design research, design theory, and design practice than design *outputs*.

Design *outputs* and design *outcomes* have often been naively conflated. The following sections distinguish between them in more detail.

Design Outputs

Design outputs are the immediate result of design activity, i.e., they are the outputs from design activity of the designer(s), design agency or organisation. Design outputs typically comprise the images, computer documents, files, drawings, instructions, specifications and diagrams signed off by designers and handed over to sponsors of a design project as shown in Figure 4.

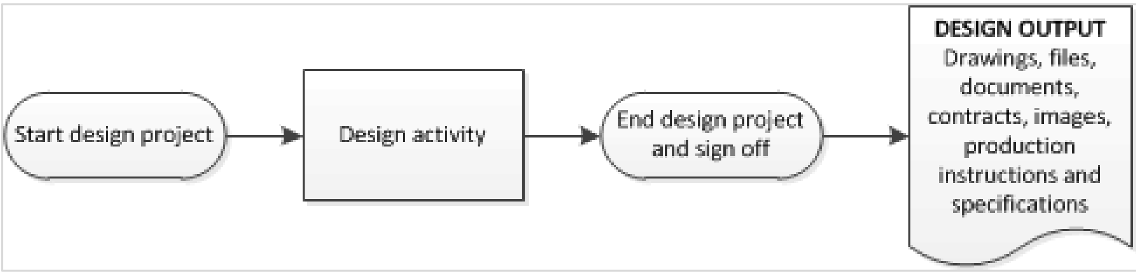

Figure 4: *Design Outputs.*

In short, design *outputs* are physical information media containing the information how to manufacture or implement to actualise the design exactly as intended.

1. *Actualized product: Volkswagen Golf car*
The design *outputs* used to create the actualized product, the Volkswagen Golf car itself, are the drawings, computer files and specifications for manufacturing it.

2. *Actualized product: Harry Potter book available to purchase in a shop*
The design outputs are the drawings, computer files and specifications that are needed to print and distribute copies of the Harry Potter book.

3. *Actualized product: Health promotion posters to put on walls in doctors' waiting rooms*
The design outputs are the drawings, computer files and specifications for printing the health promotion posters and the instructions for distributing them and placing them in doctors' premises.

To recap, real world cars, posters, books, mobile/cell phones, etc. are the *actualised products* we buy and use. The design *outputs* used for each are the physical information media holding the *designs*, the instructions for making or actualising them as shown in Figure 5.

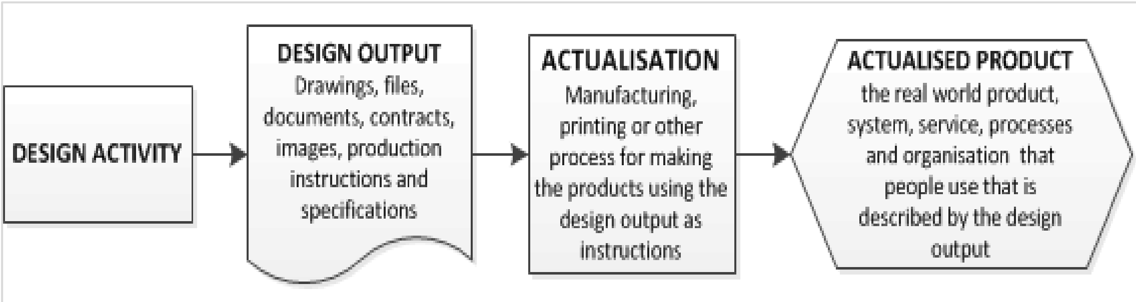

Figure 5: *Actualized product distinct from design output*.

A key, and often overlooked, aspect of both design outputs and actualised products is they are constant in time. For example, all actualised products that result from the particular design output that describes how to manufacture a particular car, book cover or typeface are intended to be the same regardless of when they are produced. In fact, a sign of the quality of a design process is that the actualised products that result from the design output are as identical as possible regardless of time.

Design Outcomes

Design *outcomes* are *dynamic* consequences in the world, the subsequent effects, of the use of products, systems, services, processes, organisations and the like created using the specifications of design *outputs*. This relationship is shown in Figure 6 below.

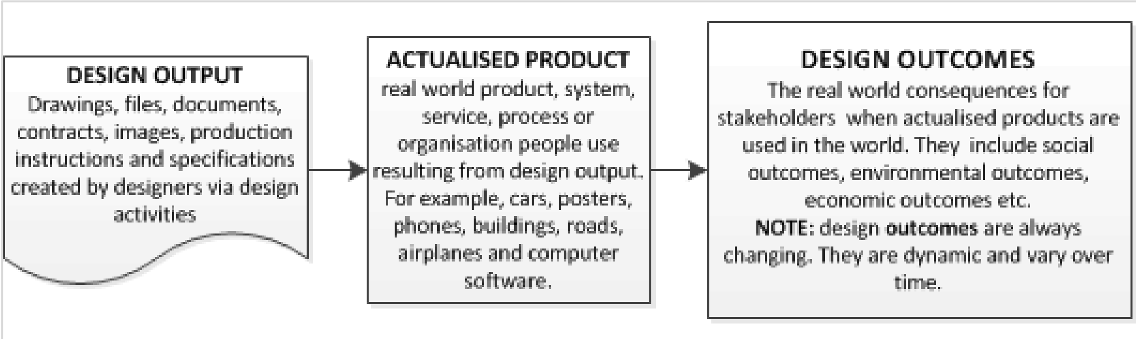

Figure 6: *Design outcomes resulting from design outputs.*

This means design *outcomes* are both practically and epistemologically different to design *outputs*.

To recap, design *outcomes* are the continuously changing consequences of actualised designs used in the world that affect stakeholders, stakeholder groups and all others as a result of the actualised designs.

Typically, design *outcomes* are found under the headings of;

- Social outcomes and impacts
- Environmental outcomes
- Economic outcomes
- Technological outcomes
- Organisational outcomes
- Ethical outcomes

Two key aspects of design *outcomes* are they are most commonly both multiple and dynamic. That is, design *outcomes* change over time. They are not constant (unlike design *outputs*).

This is an important issue and overlooking it has been a widespread failure in design education, design practice and design research. Predicting the dynamic consequences of actualised designs, the design *outcomes*, that result over time from actualised design *outputs*, requires techniques and designerly skills and knowledge than are often missing from design education, design practice and design research.

To recap, design *outcomes* are typically multiple and dynamically changing, and they result from actualised design *outputs* that are primarily static. Predicting design outcomes requires a different suite of design methods, design-related theories and design research practices than those commonly taught in design schools and used by designers and design researchers.

Importance of Design Outcomes for Sponsors and Stakeholders

Design sponsors and stakeholders are the current and future individuals and groups that have a direct or indirect interest in the consequences of design outputs (or design projects) on themselves. Design *outcomes*, the consequences in the world that result from the actualisation of a design, are the primary interest of sponsors and stakeholders.

For example, the primary interest of a publisher as the sponsor of a new design for a book cover is in the *outcomes* of how many extra readers and purchasers result from the new cover. Any interest in the appearance of the new book cover, the design *output*, is entirely subservient to this. Similarly, the primary interest of motor manufacturers is in the design *outcomes* resulting from a new vehicle including: the number of sales, the profitability, the reliability and the level of brand loyalty. For the motor manufacturers, actual appearance and design of the vehicle, the design output, is entirely secondary and in many ways, irrelevant. Similarly, again, other motor vehicle stakeholders such as the road safety industry are primarily interested in the design *outcomes* of reductions in road injuries and deaths from a new vehicle. The actual design details of the new vehicle, the design outputs of the vehicle designers are secondary to this.

This primary focus on design *outcomes* is also true for the vehicle purchasers. Their primary interest in design *outcomes* is in how well the new vehicle serves them in terms of their status, the emotions the vehicle generates, the vehicle’s functionality etc. The exact details of the vehicle design, the design outputs of the designers, are entirely secondary and in most cases often entirely unknown to vehicle owners. This can be seen in lack of knowledge about (say) how many computers vehicles have and the computer code that is in them, how the power train operates, the kinds of curve families used for the vehicle shape and the reasons for particular car body structures.

All this obvious need to focus on design *outcomes* is contrary of the self-interested persuasion and pressure by designers, and the design field in general, on sponsors and users to focus only on the design outputs, i.e., the outputs of the designers.

Following from this, it is deictically self-evident from review of the design and design research literatures that design practice and design research in most design fields have not paid significant attention to focusing on design *outcomes*.

Instead, the focus of designers and design researchers has been primarily on design outputs, i.e., the detail of the design produced by designers as described in e.g., visual representations, drawings, images and computer files. This deliberate distortion by the design field to avoid focusing on the importance of design *outcomes* has historically resulted in design sponsors and stakeholders, regardless of their natural primary interest in design *outcomes*, to be forced to interpret the value of designers' activities and choose between designs only through the lens of design *outputs*. *This problem presents a deeply embedded failure in design practice, design education and design research.*

Increasingly, however, this lack of attention to *design outcomes* in design practice, design education and design research is emerging as problematic. Evidence of this change can be seen in, for example, architecture where increasing awareness of the importance of post-evaluation surveys is a pointer to the realisation that *design outcomes* are the central concern in architecture. How a building affects people's lives (the *outcomes*) is in the end more important than the appearance or structure of the building.

The need for a transition to focusing on design *outcomes* rather than outputs is also evident in the increasing importance of evidence-based evaluations of *outcomes* resulting from medical procedures rather than the simply focusing on the design of the medical procedure as an *output* of a design process.

The significance of *outcomes* and the relative irrelevance of design *outputs* is also emerging widely in all forms of design projects that have social, environmental and economic consequences. This increasing awareness of the significance of *outcomes* can also be seen to be emerging in advertising and marketing where the *outcomes*, the commercial, economic and other consequences or benefits, are more important than the nature of the design outputs.

To summarise, design *outcomes* offer a better foundation for design research, design practice and design education, and this in turn requires reducing the current overweighting of interest in design outputs, i.e., the details of designs. By changing the focus onto design *outcomes*, stakeholders can identify the design outcomes they prefer. Then the role of designers is clarified - to be primarily that of identifying the details of a design (the design *outputs*) that will fulfil those design *outcomes*.

As identified earlier, the development of design methods to predict the dynamic consequences of design outputs is not yet sufficiently well addressed in design research, design theory and design practice or taught in design education. This is evident by the ways that, as a matter of course, to date, design *output* details are pushed as a substitute for design *outcome* predictions.

The implication is there is a widespread need in design practice, design education and design research for methods of *predicting* design *outcomes*: the dynamically changing social, environmental, economic and other consequences resulting from the details of design outputs. This key issue is addressed in the next section, where it is also argued that *prediction* is an essential and central aspect of design activity that is currently almost completely missing from design research, design theory, design practice and design education discourses.

The Essential Role of Prediction in Design, Creativity and Art

Prediction is perhaps the most essential aspect of the practice and theory of design, creativity and art. This is true at all scales, from the smallest intuitive embodied movement or thought that contributes to a design, other creative act or piece of art, right up to the largest scale of policy or strategy design decisions shaping the future of the universe.

1. *Example. An artist drawing a line or choosing a colour*

For the artist, knowing or feeling whether what they are doing, or have done, is good, or deciding to change it, is always at some level based on some kind of prediction of consequent *outcomes*. Often, however, this prediction activity is overlooked or happens so subconsciously that artists have difficulty perceiving it. Commonly, it is over-simplistically and uncritically called *intuition* or judgement.

2. *Example. Creative writing*

When an author is involved in creative writing, each word or phrase is always automatically tested against a subconscious or conscious prediction of its consequent outcomes including how the story will unfold, its effects on readers and whether it will be considered of good quality. Creative writers often conceptualise this prediction of outcomes simplistically as *the ability for the story to tell itself*, the *voice* of a *character* or *narrative flow* - all methods of prediction of outcomes.

3. *Example. Design decisions*

In any design activity, designers are faced part-way through the design activity with decisions choosing which ideas to progress and how. These choices, however, apparently subconscious, or to do with *feeling* or *intuition*, are based on some form of predicting which design decision is likely to lead to better *outcomes* in some way.

Each of the above examples shows the essential requirement for prediction of *outcomes* during the activity. Without prediction of outcomes, design, creative activities and art would be impossible and irrelevant.

The literature of design research and theory making has, however, to date concentrated on design processes, user interactions with products/services, and creativity — see, for example, Love, 2000— and substantially ignored the essential role of predicting outcomes. This latter foundational aspect of design activity, the central and key role of prediction of outcomes in design activity, has been almost completely overlooked in design research, design education and design practice.

The essential role of prediction is always tightly linked to *outcomes*. The purpose of creating any design is to create instructions to make or do something that will make a change in the world (making a product, service, building etc.) that is intended to have particular consequences, the design *outcomes*.

For example:

- The purposes of creating the design of a new book cover are to make the printed book attractive to potential buyers, to increase profits for the publisher and author, and perhaps make other changes in the world.
- The purposes of designing a new consumer product are for the manufactured product to be attractive to users, make profit, make users' lives better etc.
- The purposes of creating a design for a government social support system are to enable chosen government policy outcomes, improve outcomes for those needing social support etc.

In each of these cases and for all designs, the intention of the design is always to create some changes in the world, *outcomes*, as a result of the things or services created from designers' *outputs*. Successfully and correctly predicting such *outcomes* in the world is central to almost all aspects of design activity.

At the small scale, within the design process, prediction of likely outcomes is essential to guides designers in decisions made both of conceptual and detail design.

For design sponsors, it is prediction of outcomes that guides them in deciding whether to fund particular design activities, to choose particular designs for manufacture, or to develop particular services.

The importance of prediction of outcomes from design outputs can also be seen self-evidently from adverse consequences when prediction of outcomes is not implemented, or is partially or incompetently implemented, or fails:

- Products that no-one wants to buy
- Services that don't work, or don't work as intended
- Difficulties for users
- Problems for stakeholders
- Appearance of adverse unexpected side effects (toxicity etc)
- Catastrophic environmental effects
- Economic, financial and commercial failures
- Faulty government policy implementations
- Failure of design businesses

More broadly, prediction of outcomes is an essential skill for professionals in all fields and . central to any purposeful activity. Undertaking activities without the ability to predict outcomes is professionally unethical. To summarise, prediction of outcomes has an essential and central role in all design activity. It is an essential and foundational element of design research, design theory, design practice and design education that has currently been almost completely overlooked in many design fields.

With this understanding that prediction of outcomes is a central and essential aspect of all design activity comes the question of how human designers do that prediction and what are the limits to their abilities. The next section draws attention to human biological limits on ability to predict outcomes of design decisions.

Human Biological Limits of the Ability to Predict Outcomes

Humans have biological limits on their abilities. While this is widely accepted in relation to many physical human attributes — for example, people cannot jump 50m into the air without proper gear, pick up 2000kg or run a kilometre in a second— much less attention has been paid to the equally physical limitations of human thinking, creativity and ability to predict outcomes of particular situations.

In general, attention to such physical limits of human thinking, creativity and mental prediction has focused only on either demonstrating unusual abilities such as ability to do mental arithmetic, creative art that has surprised people or some generalist attributes of memory — e.g., remembering 5 items plus or minus 2— techniques to improve memory and mental illusions and delusions. The large bodies of philosophical, biological, psychological and cognitive neuroscience literatures on human mentation appears to have shied away from the idea that in some areas there are clear well-defined physical boundaries in mental abilities that apply to all humans. Cognitive neuroscience has identified several phenomena in this area such as the cognitive limits associated with lack of emotional participation in decision-making identified by Damasio in the 1990s (Damasio, 1994; 2000; Dennett, 1995; Love, 2003; Mosca, 2000; Sloman, 1998).

Yet physical boundaries that limit thinking, creativity and mental prediction of outcomes are clearly visible across the human realm of activities (Snowden & Boone, 2007) and especially those of design activity.

To explain further, it is helpful to make a separation and classification between four types of situations: simple, complicated, complex and chaotic. This follows the convention used in systems analysis and complexity theory and especially the Cynefin Framework of Snowden (Snowden & Boone, 2007).

These four categories of situations are defined primarily on the basis whether the situations have feedback loops and how many. In short, a feedback loop is a causal pathway by which one variable influences other variables that in turn influence the original variable itself, forming a loop of causality. A classic example is the temperature control in a refrigerator as shown in Figure 7 below.

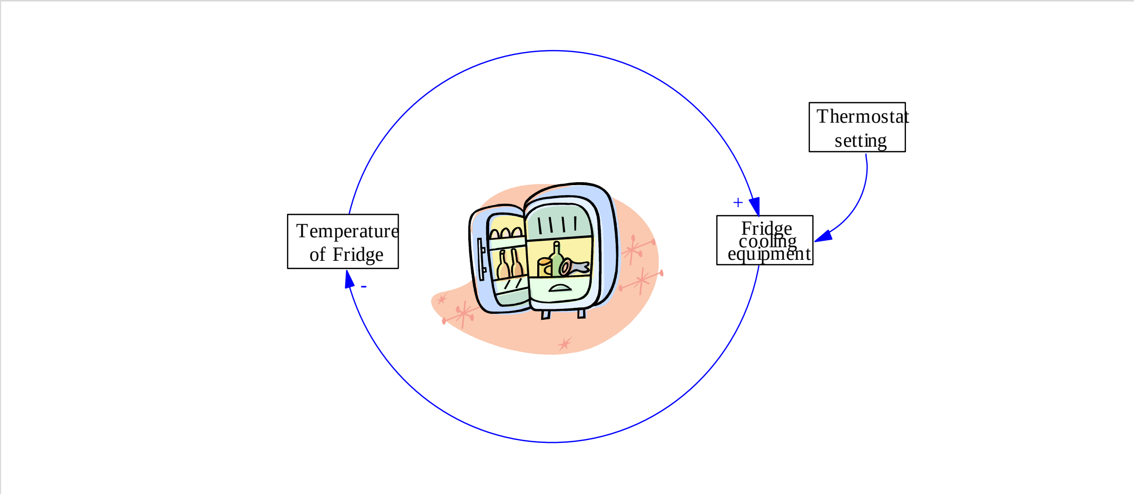

Figure 7: *Single feedback loop control of temperature in a refrigerator.*

If the temperature of the fridge is too high compared to the thermostat setting, it triggers the cooling system until the temperature is at the thermostat setting, when it turns off the cooling system until the next time the temperature rises.

This kind of feedback loop tends to stabilize the situation. Other kinds of feedback loop, for example the increase in the number of infections of people with COVID-19 by people already infected, tend to result in ongoing changes over time.

Simple Situations

Simple situations have the following properties;

- A relatively small number of elements
- A relatively small number of relationships
- The causality or sequence of behavior has a maximum of one feedback loop, and typically no feedback loops

This kind of simple situation is shown in Figure 8.

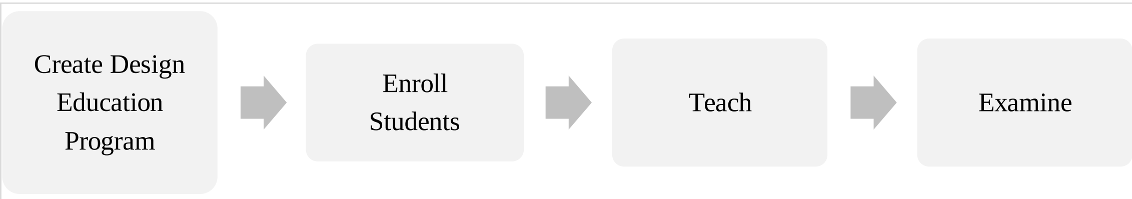

Figure 8: *Example of a simple situation.*

It is a *simple* situation because it has a low number of elements (4), a low number of relationships (3); and sequence of behaviors or causes with no feedback loops.

Complicated Situation

Complicated situations have the following properties;

- Any number of elements
- Any number of relationships
- Causality or sequence of behavior has a maximum of one feedback loop

One example of a complicated situation is shown in Figure 9 below. This is a complicated situation consisting of multiple simple situations.

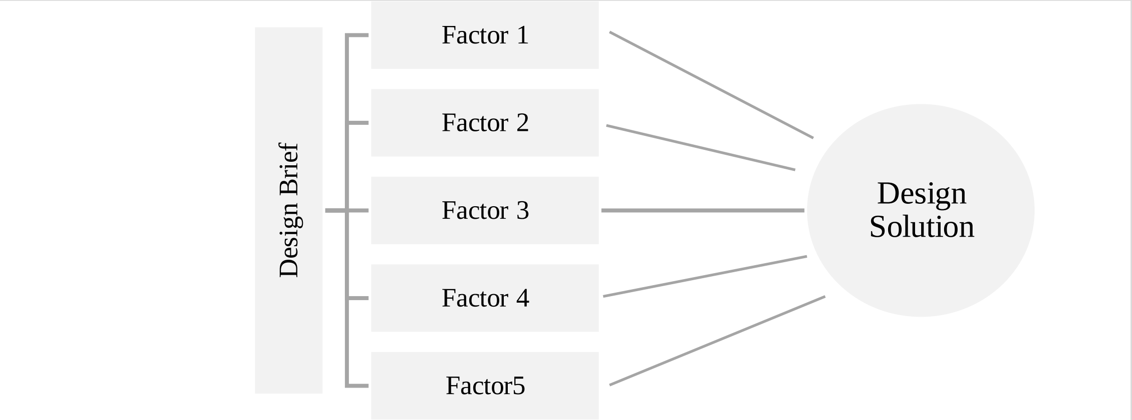

Figure 9: *Example of complicated situation consisting of multiple simple situations.*

Another example of a complicated situation is shown below in Figure 10.

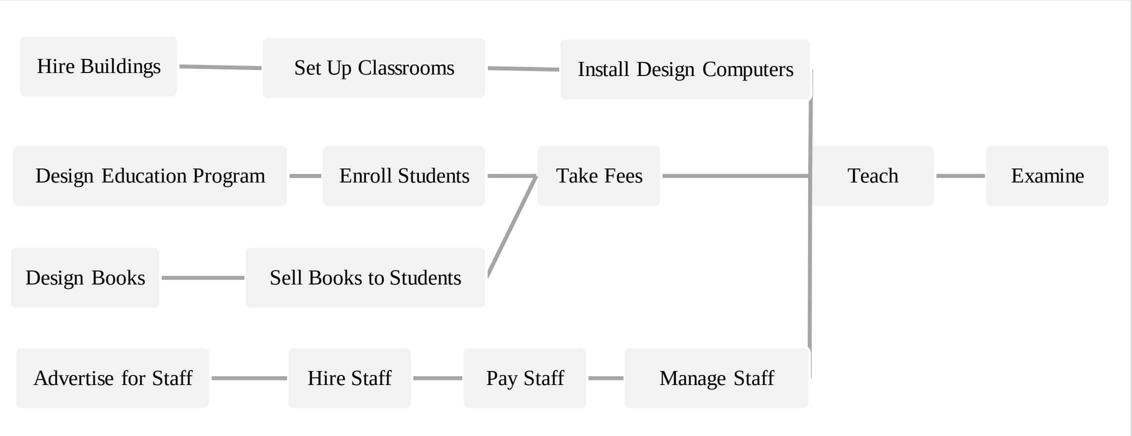

Figure 10: *Another example of a complicated situation.*

The above are *complicated* situations because they have a larger number of elements and relationships compared to simple situations and have one or less feedback loops. In the above cases, they have no feedback loops. An example of a complicated situation with one feedback loop is shown in Figure 11 below.

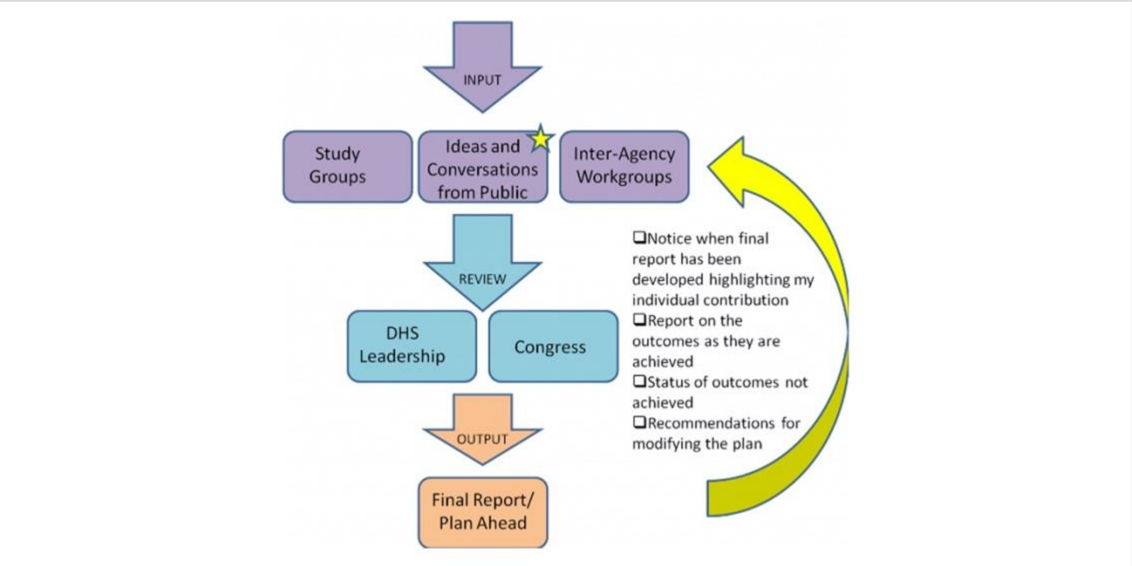

Figure 11: *Example of complicated situation with a single feedback loop.*

Complex Situations

Complex situations have the following characteristics;

- Any number of elements
- Any number of relationships
- Two or more feedback loops
- Outcomes can only be predicted by mathematical modelling, analogical modelling or similar non-mental process.

An example of a diagram of a *complex* situation is shown in Figure 12 below.

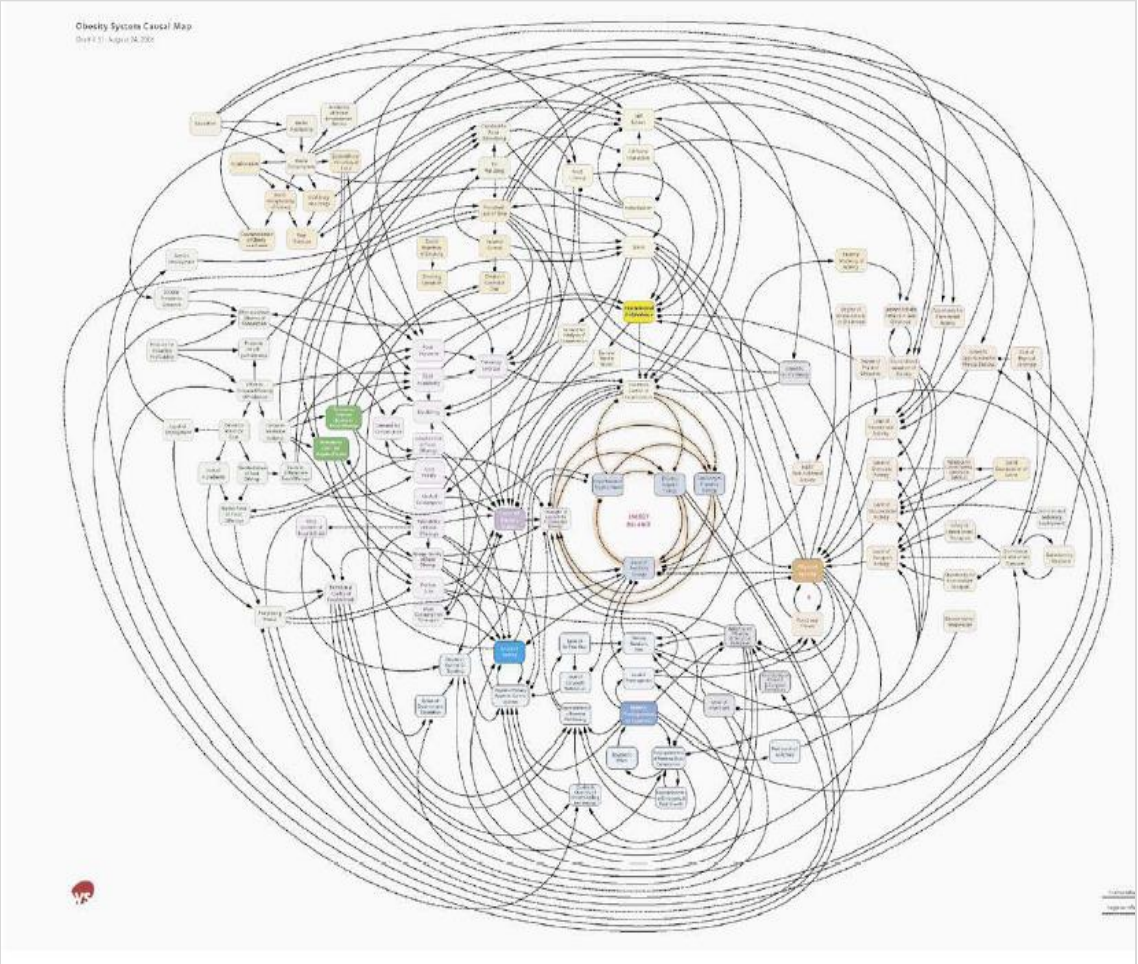

Figure 12: *Example of a complex situation of causes and interventions of addiction*.

The example of a complex situation above has a relatively small number of elements with a larger number of relationships. Importantly, it has more than one feedback loop — in fact it has many feedback loops—and it is this latter factor and the potential for the outcomes of the situation to be predictable only by mathematical or other non-mental modelling that makes this a complex situation.

Chaotic Situations

Chaotic situations are characterized by the following;

- Any number of elements and relationships
- Two or more feedback loops
- Outcomes cannot be predicted by modelling

In essence, a *chaotic* situation is a situation in which the type, combination and timing of feedback loops means that prediction of outcomes is intrinsically not possible. Sometimes such systems are sensitive to initial conditions, or have random elements to their behavior, or minor variations in internal systems that influence feedback loops such that it becomes impossible to predict outcomes. Practical examples of such chaotic systems include ball and shaker mills used in the processing of ore and the movement of vibrators used in laying concrete.

There are several mathematical measures that can be used to define whether and why complex systems have intrinsically unpredictable chaotic behavior of outcomes. However, these are somewhat limited (Bishop, 2017) and in the limit it becomes unclear whether a *chaotic* situation is merely a *complex* situation for which there is as yet no practical methods of modelling and prediction of outcomes.

Biological Limitations to Thinking, Creativity and Prediction of Outcomes

Using the above categorization of simple, complicated, complex and chaotic situations or systems, the author has previously reported (Love, 2010; Love, 2010) findings that humans are *unable to predict the outcomes of complex or chaotic situations*. That is, there appears to be a physical limit on the ability of humans to understand and mentally predict the outcome behaviours of situations and systems with two or more feedback loops.

The author has called this the *Two Feedback Loop Limitation*. It aligns with and is supported by previous analysis by others including Forester and Sterman (Forrester, 1971; 1972; 1975; Sterman, 1991; 2002).

Love also suggested that not only are humans, regardless of skill, training, intelligence and collaboration with others, unable to mentally predict the outcomes of such complex and chaotic situations, when they try to do so they mentally delude themselves that they understand the behaviour of such systems and have accurately predicted the outcomes - when it is evident they are mistaken (Love, 2010; Love, 2010).

To summarise, the current evidence indicates there are classes of situations having two or more feedback loops, that humans, regardless of the quality of their abilities, are unable to mentally predict accurately the outcome behaviours and yet internally are mentally deluded that they have the ability and have correctly done so.

The above criterion, the Two-Feedback Loop Limitation, also usefully defines a boundary for categorising design thinking methods.

Three Categories of Design Thinking Methods

Reviewing the design literature across the last 70 or so years it is clear the phrase *design thinking* is etymologically wide ranging and ambiguous in its meaning: and not merely because of the widespread lack of agreement on the exact meaning of the word *design*.

Where humans conduct design activities, they do this through some form of thinking, regardless of whether it comprises neurally-based images in the brain or some broader-based thinking activity involving more of the body, including affective, feeling activities, postures and physical movements as embodied cognition. Thus, in its broadest sense, *design thinking* could be considered an equivalent or synonym for the verb *design*; and with *design thinking method* the equivalent of *design method*. The analyses in this paper suggest it is useful to divide design thinking methods into three distinct and non-overlapping categories.

Echoing the categories of design situations presented in the previous sections, a starting point is to classify design activity into:

- Routine design
- Complicated design
- Complex design

Routine Design

Most *routine design* does not require the same sorts of design thinking as the processes of the Stanford/IDEO design thinking method. Typically, *routine design* is the creation of a design — as a specification for making and doing things— that humans already know how to do. That is, in routine design we already know the best, or at least the satisficing, routine design for a specific outcome.

Such *routine design* can perhaps be seen most easily in graphic design, product design, architecture, electronic design of circuits and computer chips, and mechanical engineering design. In graphic design it can be seen in the implementation of the rules of design taught in design schools that are matters of routine design decisions for human designs to the point they have now been embedded deeply into automated design processes in graphic design software such as Adobe Photoshop. Two obvious examples are the rules for placement of text and graphics on pages and the metrics for setting text. In product design, such routine design emerges in for example the guidelines for designing web pages.

In architecture, routine design is embedded to the point that architects retain the ownership of clients' designs and can reuse all or part of them, and there are standard design specifications for many design details including brick sizes, concrete mixes, lift shafts, bathroom layouts, hospital layouts and exit arrangements. In electronic circuit design, there are standard design solutions for amplifiers, logic circuits, control systems and computer chip elements. In engineering design, routine design is widely developed to the point where there are internationally agreed standards for concept designs and design details in for example pressure vessels, nuclear reactors, bearings and gears.

In this *routine design* form of design thinking, prediction of outcomes is reversed from the approach in other modes of design thinking. It is the *outcomes* that define the routine design solutions – often via standards or widely accepted conventions by which from long experience, or from testing leading to standards, enable designers and stakeholders know without any prediction process the consequences or design *outcomes* of such routine design *outputs*. For example, the lifetime of a marine component galvanically coated with zinc to a certain standard is routinely known from that standard without any need for a special prediction process.

Complicated Design

These are design activities that, regardless of the complicatedness of causal relationships, the design outcomes can be predicted by humans mentally . Sometimes it is necessary to provide designers, sponsors and stakeholders with some support to understand the relationships — for example Bob Horne's diagrams, http://bobhorne.us—. However, regardless of the difficulty, for complicated design situations there appears to be no intrinsic limit on human designers' and others' abilities to mentally predict the outcomes.

Complicated design situations are the primary target for the Design Thinking method of Stanford and IDEO. In the Stanford/IDEO Design Thinking method, participants are invited to follow the path illustrated earlier in Figure 1, typically using the recording methods of Figure 2 to create a rich picture from which participants can propose and decide between design decisions and solutions on the basis of their ability to predict the outcomes of such decisions.

Complex Design

Complex design situations present distinctly different requirements for design thinking from those for routine design or complicated design situations.

Complex design situations are characterised by multiple feedback loops. As a result, outcomes and consequences cannot be mentally predicted due to the biological limitations of human cognition. In addition, the outcomes of complex design situations are typically dynamically changing over time due to the interaction of feedback loops. This is a significant difference from routine design and complicated design situations.

For such complex design situations, the Stanford/IDEO model of design thinking does not apply. This is because the Stanford/IDEO design thinking methods depends totally on participants' ability to mentally predict or intuit outcomes resulting from design decisions, and this is not possible for design situations with 2 or more feedback loops.

This limitation also applies to groups of stakeholders and design team participants as well as individuals. Biologically, none of the members of such design teams can mentally predict outcomes so the whole team cannot either. Hence, there is no benefit in having multiple participants over a single participant in terms of the ability to predict outcomes. This latter observation challenges the validity and professional ethics of using participative, collaboratory, co-design and similar design methods for complex design situations.

Taken together with the earlier analyses, the above points to a useful separation of design thinking into three very different categories;

- Design thinking for *routine designs*
- Design thinking methods for *complicated* design situations whose outcomes can be mentally predicted either by an individual or group. The Stanford/IDEO design thinking method falls into this category, which overlaps almost completely with the class of participative design providing such participative design fully excludes designing for complex and chaotic situations.
- Design thinking methods for *complex* design situations whose outcomes cannot be mentally predicted by individuals (or groups of people) because of the biological limitations of human cognition and intuition for situations with 2 or more feedback loops.

For brevity, I've called these three categories:

- Design thinking for routine design
- Design thinking for complicated design
- Design thinking for complex design

Each of these categories of design thinking methods are described in detail below.

In each case, the design process starts, or in almost all cases should start, — and I use that *should* very specifically and deliberately—, with identification of the intended *outcomes*. Without this, any professional design process is unprofessional and unethical. In other words, the *outcomes* intended to result from design *outputs* actualised in the world, should define both the problem framing for the design process and the decisions about the selection of concepts and design details.

Design Thinking for Routine Design

In design thinking for routine design, the paths from the identification of intended outcomes to decisions about the design framing and selection of the concepts and deign details of the design solution are both short and obvious. Design thinking for such routine design decision making is defined by existing codified knowledge and data and assumes the design situation is either simple or complicated and explicitly neither complex nor chaotic.

For example, an intended outcome of part of a design for a residence is that the roof should have a reasonable life. The design situation is simple: the roof is acted upon by climate and weather and is expected to last a certain time The problem framing for selecting a design solution will include that the roof should last more than 25 years in that the climate and weather at that location. Reference to manufacturers catalogues along with material and building standards and weather and climate records and predictions will define a shortlist for selecting a design solution. Once that design solution is chosen, the standards will define all the design details in a routine manner. The design thinking process is in essence to follow the current evidenced design knowledge from design outcome to design problem framing to selection of design solution.

Design Thinking for Complicated Design

This second category of design thinking methods includes all those design methods where the *outcomes* resulting from the things created from the designs are mentally predictable.

There are many design thinking methods in this category. Previously most of these design thinking methods were simply called design methods. The design thinking method developed in Stanford and IDEO and taught in the Hasso Plattner Institute of Design at the Stanford d. school is currently perhaps the most well-known of the design thinking methods in this second category aimed at complicated design situations with only one or no feedback loops.

These kinds of design thinking methods for complicated design are unsuited to, and fail, if they are used in design projects involving *complex* design situations.

The above exclusion of these design thinking methods from *complex* design situations is important and a significant change in design theory and theory about design methods; especially methods of participative design, consultative design, co-design, stakeholder participation ion design multidisciplinary design, community consultation in design and any design methods that involve human designers and stakeholders. To make it clear, *Complex design situations whose outcomes cannot be mentally predicted CANNOT be professionally, ethically or competently designed using any kind of design thinking methods devised for routine or complicated design situations.*

This is a major and apparently unavoidable limitation of the Stanford/IDEO design thinking method. To summarise:

- If a designer cannot mentally predict the outcomes resulting from any design decision, then they do not know the consequences from those design decisions. This means they have no idea what the results of the design will be. It implies any designing using such a design method is unprofessional, unethical and incompetent.
- Importantly, also, in design theory terms, if an individual cannot mentally predict the outcomes resulting from a design decision about a complex situation — due to the intrinsic human biological limitations— then there is no benefit in any way in involving multiple people — i.e., using participative, collaborative, co-design or similar design methods—. Because generic human biological limitations mean that humans cannot predict outcomes of design decisions for complex situations with 2 or more feedback loops, then it is just as impossible predicting the design outcomes using multiple people: none can predict the design outcomes.

Design Thinking for Complex Design

Three key factors that characterise complex design situations are:

- *Outcomes* resulting from the use of design things or services are dynamic and shaped by two or more feedback loops — the above definition of a complex situation—.
- *Outputs* of such complex design situations cannot be mentally predicted by humans because of the apparent physical biological limitation of human brains, emotion and intuitions in being able to predict the behaviour of situations with two or more feedback loops.
- Design thinking methods that depend on human design thinking — i.e., for routine design and complicated design— do not apply in complex design situations because they do not work.

However, there is another class of design methods and a different kind of design thinking process that are effective in complex design situations involving multiple feedback loops.

At the heart of such design methods is dynamic modelling (usually mathematical) of both the actualised designs and their complex environment such that the *outcomes* in the real world resulting from design decisions can be observed by designers and other stakeholders in changes to the dynamic behaviours of the model.

Because the dynamic model creates the predictions of outcomes , the lack of human ability for designers and stakeholders to be able to individually mentally predict such outcomes is no longer problematic.

In other words, design methods for complex design situations are based on the externalising the prediction of the dynamic consequences resulting from design decisions. That is, by creating a dynamic model, or digital twin, of the design situation and world, designers and stakeholders can observe the consequences and *outcomes* of design decisions without needing to mentally understand or predict why or how these occur. In essence, design thinking methods for complex situations contains the following steps:

- Identify the situation, problem and intended outcomes at a general level.
- Identify stakeholders and local knowledge holders for all aspects of the situation and problem.
- Gather information from stakeholders about all aspects of the situation and problem as initially perceived. Reconceive the problem situation as necessary and repeat until agreement the information is complete.
- Use the information provided by stakeholders and local knowledge holders to create a complete causal loop diagram or similar that includes the key elements identified by stakeholders and local knowledge holders and the causal relationships that influence behaviours of each of those elements. Note: individual stakeholders and local knowledge holders will typically only know conditions and relationships for part of the causal model. Hence the complete causal loop diagram will be assembled from different partial causal loop diagrams representing the knowledge of different participants. Coherence in the causal loop diagram at points of overlap between participants knowledge offers a test of integrity of both the diagram and the participant knowledge.
- Review the causal diagram with stakeholders and local knowledge holders to ensure it includes and does not contradict their understanding — necessary and sufficient test—.
- Create a system dynamic model based directly on the causal loop diagram and with the local knowledge being used to identify the coefficients for the equations describing the causal relationships.
- Calibrate and test the system dynamic model for key boundary conditions identified from stakeholders and local knowledge holders and confirm with them that the model behaves in a similar way to the real-world situation — modify the model if necessary—.
- Then, designers, stakeholders and local knowledge holders can speculate on possible design solutions.
- The resultant design outcomes for each of the proposed design solution can then be identified using the system dynamics model and a preferred solution be chosen on the basis of the predicted outcomes.

The above approach completely addresses the combined problem that humans cannot predict the outcomes of design decisions for situations involving two or more feedback loops (complex situations) and that prediction of outcomes is essential to any design undertaken professionally and ethically.

In complex situations with multiple feedback loops, the design solutions proposed and chosen are often better seen as *design interventions* rather than design solutions. This is because any situation involving multiple feedback loops is dynamic, that is the situation, and *the outcomes are changing over time* and thus the consequences of a design output act more like an intervention rather than a solution.

In other words, in complex situations, there are no fixed outcomes that can be compared between design solutions. Instead, design decisions about a design solution/intervention are made on a choice between the continuously changing future trajectories of the situation – with outcomes often sometimes getting better and sometimes worse over time.

The above design thinking method for complex design has multiple advantages. The design process is straightforward although it is very different from the design thinking methods for routine design or complicated design and different to the Stanford/IDEO design thinking method. However, the processes within the Stanford/IDEO design thinking method can be used to provide the information necessary to create the mathematical dynamic model and provide the information for calibrating such a model in complex design.

It is perhaps worth observing that this category of design thinking method for complex design can also be legitimately used and applied to both routine design and complicated design. However, it is expensive in time and resources to do so.

Implications for Design Outcomes, Theory, Practices and Education

The analyses in this paper provide exclusive criteria for categorising different design thinking methods against three different categories of design situations. The analyses reveal three different categories of design thinking for routine, complicated and complex design situations of which the design thinking method of Stanford / IDEO is appropriate for routine and complicated design situations but not complex design situations. The analyses leading to the separation of design thinking methods into the above three mutually exclusive categories offer significant potential benefits in improving design practices and outcomes.

First, they point to the essential and central role in prediction, particularly of design outcomes, in all design, creativity and art.

Second, they draw attention to the importance of the ability to *predict outcomes resulting from designs* as perhaps the most important aspect of design activity.

Third, classifying design thinking into three categories on the basis of three specific classes of design situation supports designers and stakeholders to improve the value of design activity by creating better design outcomes whilst avoiding design failures, wasting of design resources and time and avoiding professional ethical problems.

Four, the class of design thinking methods identified as suitable for complex design situations provide a consistent reliable and effective method for finding the provably best solutions for addressing wicked problems.

Five, this new classification of design thinking methods on the basis of the four categories of design situation provides a new basis for design researchers to identify foundational aspects of design thinking and design methods in general.

Six, and perhaps most obvious, a benefit of the above analyses for design research is to focus research attention and theories about design process on the essential role of prediction of real-world outcomes that result from specific design decisions about design concepts, details and actualisation.

Seven, the analyses in the paper open up a new approach to developing and using new design methods and design research projects for addressing complex situations where design outcomes depend on 2 or more feedback loops.

Eight, the analyses in the paper also bring a critical perspective on the use of the Stanford/IDEO design thinking method. In short, it calls into question as invalid the use of the Stanford/IDEO design thinking method, and any participative, collaboratory and co-design, design method, for complex design situations where outcomes of design activities depend on 2 or more feedback loops.

Design Thinking for Wicked Problems as Complex Design Situations with 2 or More Feedback Loops

The design thinking method described above for complex design is also suitable for identifying best design interventions for *wicked problems*. In the main, the core difficulty of wicked problems has been they contain many feedback loops and conventional design methods cannot address problems that involve feedback loops. The design thinking method for complex design addresses such wicked problems directly.

Emergence of a Fourth Category: Automated Design Thinking

The above analyses and discussion have identified three distinct exclusive, non-overlapping categories of design thinking methods based on three categories of design situation with the third category defined by the human biological limitation of humans being unable to mentally predict the dynamic outcomes resulting from situations whose behaviour is shaped by two or more feedback loops.

However, design activity more broadly is nowadays substantially supported by, and many design decisions undertaken by, semi-intelligent computer systems. Many of these computer support systems for designers have for more than 3 decades been using artificial intelligence systems to make design decisions tacitly for designers. Examples include common design software from Adobe, AutoCAD and others.

Thus, the reality is almost all forms of what is naively considered 'human design thinking' includes a substantial amount of automated computer input into design decision making by using artificial intelligence systems. In many cases central to human design thinking, key design decisions are fully automated in a manner that is not visible to designers or stakeholders.

The challenge is how best to include such a reality about the computerised aspects of human design thinking in theories about, and categories of, design thinking.

This potentially indicates the need for an extension of the idea of design thinking to include such computer-based artificial intelligence. One way of doing so is to extend the idea of design thinking to include 'thinking' provided computers. In other words, to extend the concept of design thinking beyond humans to include non-human actors.

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