# Collaborative problem–solution co-evolution in creative design

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*Creative design concepts are often viewed as developing iteratively, with the design problem and solutions 'co-evolving' in a mutually adaptive manner. We report a study examining whether the co-evolution concept captures the creativity arising in collaborative, team-based design practice. The analysis revealed that co-evolution episodes occurred regularly and embodied various directional transitions between problem and solution spaces. Moreover, the team leader often initiated this co-evolution. Co-evolution episodes linked with other creative activities such as analogising and mental simulation and there was a clear association between co-evolution and expressions of epistemic uncertainty, suggesting that designers were dealing with considerable complexity and ambiguity. Our findings support the view that co-evolution is the 'engine' of creativity in collaborative design.*


*Keywords: problem–solution co-evolution, creative design, collaborative design, design cognition*

Efforts to advance a scientific understanding of the design process have given rise to many important insights over the past four decades, with a large number of these insights being reported in the pages of this journal. Arguably one of the most noteworthy ideas to emerge in recent years is that creative design concepts can be viewed as being developed through an iterative process, whereby the design problem and potential solutions 'co-evolve' over time, with the designer exploring two conceptual spaces, a 'problem space' and a 'solution space', with each space informing the other. According to this iterative, co-evolution view of design, not only do potential design solutions receive consideration in the context of the requirements that define the problem, but such requirements can also themselves be adapted in the light of novel solution attempts. As such, design problems are not fixed but are mutable, unlike the view of design espoused in the traditional 'problem solving' model (e.g., Simon, 1969), where the search for a potential solution arises in a unitary problem space that is defined by a set of relatively stable design requirements and constraints.

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The co-evolution view of design was originally advanced by Mary Lou Maher (e.g., Maher, 1994, 2000; Maher & Poon, 1995, 1996; Poon & Maher, 1997), who drew on the biological concept of two species interacting so intimately that their evolutionary fitness depends on each other. By evoking this metaphor from nature, Maher advanced an artificial intelligence (AI) understanding of the way in which design problems and design solutions can both be modelled as evolving separately while having a mutual effect on one another. Subsequent to Maher's pioneering computational research on problem–solution co-evolution the concept has since gained particular momentum following Dorst and Cross's (2001) *Design Studies* article, which applied Maher's computational concept to a behavioural analysis of human creativity in the design process. Dorst and Cross proposed that their empirical data deriving from verbal protocol studies of experienced industrial designers corroborated the general validity of the co-evolution model. The Dorst and Cross (2001) article is now the second most cited paper in the present journal's history, with 218 citations recorded in Scopus (accessed 12 January 2013), attesting to the appeal and impact of the co-evolution concept.

Despite such widespread recognition of the apparent importance of problem–solution co-evolution in design, it is perhaps surprising that few follow-up studies can be found in the literature that systematically test the generality and applicability of the construct across different design domains, problem types, expertise levels and data collection methodologies. In the present paper we aim to advance research on problem–solution co-evolution by examining the capacity of the concept to capture aspects of creativity in professional, team-based design practice. It is the examination of co-evolution in *collaborative* design that we would argue represents one of the key elements of originality in our reported research. Before considering the specific aims and methodology of our study, however, we first examine the concept of problem–solution co-evolution in more detail so as to clarify the context and rationale for our own empirical contribution.

## 1 Problem–solution co-evolution in design: the computational perspective

Maher (1994; see also Maher & Poon, 1996) was the first researcher to propose a co-evolution model of design as involving an interaction between the problem space (i.e., the required behaviour of the design) and the solution space (i.e., the potential structural combinations that constitute the design). Both state spaces are viewed as interacting over a time spectrum (see Figure 1) and are assumed to be evolutionary systems, with the evolution of each space being guided by the most recent population of entities (i.e., alternative problem requirements or alternative solution possibilities) in the other space. As can be seen in Figure 1, evolution involves a horizontal process within a particular state space. On the other hand, diagonal movements reflect a search process, which can arise: (1) when the problem leads to a solution, as is the case,

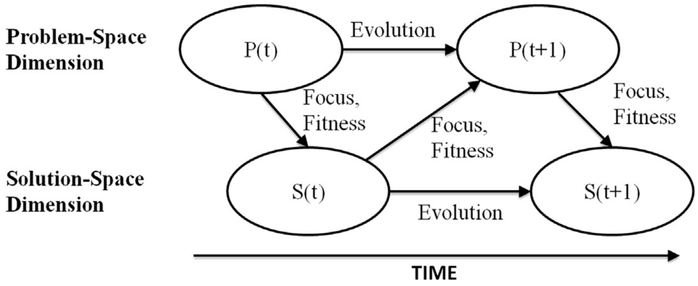


*Figure 1 A computational model of co-evolution (after Maher et al., 1996).*

for example, with the downward arrow leading form P(t) to S(t), where 't' denotes a time point; or (2) when the solution re-focuses the problem, as is the case, for example, with the upward arrow leading from S(t) to P(t + 1). This latter process is particularly interesting, and arises when a solution attempt is undertaken that does not fit the full set of requirements that constitute the current state of the problem space, necessitating the pursuit of a clarification, change or adaptation of the requirements in order to allow for the solution attempt to become a valid solution possibility.

Maher and Poon (1996) assume that the basis for co-evolution is a simple genetic algorithm that gives primary consideration to the representation and application of the 'fitness function', that is, the figure of merit that evaluates, for example, how close a given design solution is to achieving the current status of the design goal. What this means in practice is that the definition of a problem can change in response to the current status of the solution space as opposed to being fixed and defined once-and-for-all. As an integral aspect of their AI approach to design, Poon and Maher (1997) also draw inspiration from definitions of 'emergence' in relation to research on Artificial Life (ALife; e.g., Taylor, 1990), since it is vital for a co-evolutionary design process to engender 'emergence' in design behaviours and structures (i.e., as a 'global pattern' that is a consequence of the local interactions between low-level units). Poon and Maher (1997) provide a compelling proof of concept of their co-evolution and emergence approach using computational models that could solve design problems in two different domains (i.e., brace frame panel design and floor plan layout design), which they implemented as either a tightly-coupled (i.e., host—parasite) genetic algorithm or a loosely-coupled (i.e., prey—predator) genetic algorithm.

In her theorising Maher is implicitly assuming a "Universal Darwinism" approach (Campbell, 1960, 1990), extending Darwin's evolutionary theory beyond its original domain of biological evolution so as to formulate an account of the mechanisms of variation, selection and heredity in the domain of design computation. Importantly, Maher recognises that the co-evolution metaphor has a number of challenges when applied to design, such as issues relating to the precise entities in the design process that resemble the entities in a natural evolutionary system and concerns with the mechanisms that drive and select variations. Maher also addresses issues relating to the termination conditions for a co-evolutionary design process, that is, how does such a process determine when it is time to stop? Candidate stopping rules (see Maher & Poon, 1996) include terminating the solution search when: (1) a generated solution matches the initial problem; (2) time is running out; (3) an equilibrium point is reached such that there is minimal variation in the problem or solution spaces over successive iterations; and (4) the process does not converge on a single solution but repeats previously encountered solutions (i.e., the problem can be satisfied by several solutions).

## 2 *Problem—solution co-evolution in design: the behavioural perspective*

Notwithstanding the strengths of a Maher's AI model of problem—solution co-evolution in design, it remains questionable whether something akin to this model captures the reality of the 'human' reasoning process as deployed by design practitioners. Dorst and Cross (2001) addressed this issue head on in their seminal research on design creativity, whereby they attempted to determine whether their empirical observations aligned with a model of problem—solution co-evolution. Dorst and Cross's research involved laboratory-based 'think-aloud' protocol studies of nine industrial designers, all of whom were currently working in design consultancies and possessed more than five years of professional experience. The presented design assignment was to create a concept for a 'litter disposal system' in a new Netherlands train. This was viewed as a typical industrial design problem inasmuch as it called for the integration of dimensions relating, for example, to ergonomics, construction, engineering, aesthetics and business. All necessary information was provided to the designers on topic-specific information sheets that were supplied to them during the study when they asked for further information. The topics covered on these information sheets included technical details about materials and production techniques, responses arising from interviews with the client, and the summary results of a survey that had been undertaken with train passengers.

Post-study, the final design concepts that had been produced by each designer were assessed by five independent judges on a range of dimensions, with the creativity of the designs being a central concern. Interestingly, all of the designers were seen to be attracted to one particular creative idea that had been implicitly 'seeded' in the given information sheets, that is, that newspapers needed to be collected separately to other items of litter. Moreover, all of the designers viewed this as an 'original' idea that had for them the status of an 'insight' event or an 'aha' moment (see Akin & Akin, 1996). Indeed, each designer believed that this novel idea would give them a competitive advantage over the other designers, even though, unbeknownst to them, the other designers had likewise uncovered this key insight.

Of most relevance to the co-evolution model, however, was Dorst and Cross's observation that the creative design activity arising in the verbal protocols did not manifest as a process whereby the designers first fixed the problem and then searched for a satisfactory solution. Instead, creative design activity was more nuanced than this, with the designers developing and refining both the formulation of the problem as well as solution ideas through a constant iteration of analysis, synthesis and evaluation between the problem space and the solution space in a manner akin to Maher's problem–solution co-evolution model. As a case in point, Dorst and Cross describe how the information about newspaper litter that was seeded in the design assignment helped to crystallise a core solution idea for a product that could keep newspapers separate to other items of litter. This, in turn, changed the designers' view of the problem, leading to problem re-definition and an assessment of whether this redefined problem aligned with earlier solution ideas that might be modified accordingly.

Dorst and Cross (2001) represent the creative process that they observed in their study as a co-evolution model (see Figure 2) that is based on a refinement of Maher's original model. In this revised model the designer begins by exploring the problem space (PS), and finds, discovers or recognises a partial structure, P(t + 1). This partial PS structure is then used to provide a partial structuring of the solution space (SS), that is, S(t + 1). The designer then considers the implications of this partial SS structure and uses it to generate some initial ideas for the form of a design concept, thereby extending the partial structuring, S(t + 2). Some of this extension and development of the partial structuring may reflect references to previous design projects (for evidence of the role of spontaneous analogising in creative design see Ball & Christensen, 2009; Ball, Ormerod, & Morley, 2004; Christensen & Schunn, 2007). The designer subsequently transfers the developed solution structure in the SS back into the PS, that is, P(t + 2), and again considers the implications of this developed PS structure, further

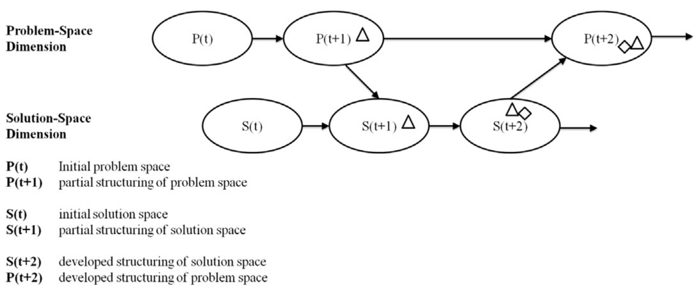


*Figure 2 Dorst and Cross's (2001) problem–solution co-evolution model as derived from the observations in their study of design creativity.*

extending and structuring the PS with the goal of creating a matching problem–solution pair.

An important upshot of Dorst and Cross's co-evolution account of creative design is the realization that the creative event is not so much a 'creative leap' from the problem to the solution as the building of a 'bridge' between the problem space and the solution space (cf. Cross, 1997), with this bridge being triggered by the designer's identification of 'surprising' information or 'interesting' points in the presented information or design brief. In this way Dorst and Cross draw a conceptual link to Schön's (e.g., 1983) notion of 'problem framing' by proposing that a creative event (e.g., an insight or aha event) occurs when a problem–solution pairing is framed. Dorst and Cross further contend that studies of expert and outstanding designers (e.g., Cross & Clayburn Cross, 1998) indicate that this problem–solution framing ability is crucial to attaining the highest levels of performance in creative design disciplines.

Dorst and Cross (2001) are not the only researchers to have applied Maher's problem–solution co-evolution concepts in advancing and understanding of human creativity in design. Maher herself has sought behavioural evidence for the co-evolution of problem specifications and design solutions using verbal protocol analysis methods (see Maher & Tang, 2003). In seeking to corroborate a co-evolution account of design, Maher and Tang did not assume that human designers would be seen to apply a genetic algorithm involving operators that implement the selection, cross-over and mutation of requirements and structures. Rather, their focus was on whether human designers could be observed to modify and shift the range of problem requirements and design solutions over time in a manner that resembled a co-evolutionary approach.

Maher and Tang (2003) reported two studies that addressed the co-evolution issue. In the first study the participants (third-year design and architecture students) were asked to provide concurrent think-aloud protocols whilst designing a novel kettle. A key focus for this design task was the need to develop an interface with the kettle that would prevent accidental scalds. The second study focused on an architectural design task, which entailed designing a house for a young couple (a female dancer and a male painter) who were described as being sensitive to colour and beauty and who enjoyed contact with the natural environment. Participants were provided with several key details of the site for the new house (e.g., location, site area, views, floor-space ratio and local climate) as well as constraints on the building itself (e.g., height restrictions, maximum floor plan and the need for a sculpture garden). The design task was to arrange and give form to the various spaces on the site (e.g., the living/dining area, the kitchen, the painter's studio, the dancer's studio etc.) using approximate area requirements that were provided in the brief. In this second study the participants were practicing architects with 30 years' experience in residential house design. Furthermore, participants were asked to design without thinking aloud and instead retrospective verbal reports were taken whereby the designers were asked after task completion to describe the details of what they had been thinking about when tackling the problem.

Maher and Tang's protocol studies provided clear evidence for all predicted co-evolutionary transitions: problem to problem; problem to solution; solution to problem; and solution to solution. The data also revealed that these transitions have a clear temporal dimension, often manifesting in cyclical oscillations between problem requirements and solutions until satisfactory solutions appear. Furthermore, the transitions between the problem space and the solution space appeared to be causal in nature, with activity in one space associating to activity in the other space in a highly interactive manner. Maher and Tang concluded that the computational co-evolutionary model of design provides a good basis for a cognitive model of design, with the two models best being viewed as complementary; the computational co-evolutionary model makes use of a relatively large memory but limited reasoning capacities, while the human designer's co-evolutionary cycles make use of a relatively limited memory but powerful reasoning abilities.

## 3 Aims of the present study

One appealing aspect of the co-evolution model of design espoused by Dorst and Cross (2001) is that it goes a long way towards de-mystifying notions such as insight moments and aha events that arise in creative design. This is because even relatively 'ordinary' co-evolutionary episodes based around a change in the problem space (driven by surprising/interesting information) and a corresponding change in the solution space (see Figure 2) can be viewed as constituting a creative episode. As such, creative episodes need not be monolithic moments of profound insight, but can instead have a more mundane flavour to them, much like what creativity researchers refer to as 'little c creativity' (e.g., Sawyer, 2012). Indeed, as Dorst and Cross (2001) note, it is often only in retrospect that a designer (or, perhaps, an observer of the design process) is able to identify a point during the design process at which a key concept started to emerge. Moreover, when studied in retrospect 'creativity' frequently becomes an honorary term that is used to refer to historically groundbreaking novelty that changed the world (so-called 'Big C creativity'; Sawyer, 2012), whereas when studied prospectively and at the micro level, what becomes evident is that creativity is a commonplace occurrence. In sum, it is entirely possible that creativity is rather common in everyday design projects and is not just the province of the activity of exceptional designers.

Despite the evident strengths of the empirical studies reported by Dorst and Cross (2001) and Maher and Tang (2003), we note that they both suffer from a potential lack of ecological validity, since the studies involved laboratory-based observations over highly time-limited design sessions (e.g., 2.5 h in the Dorst and Cross study). As such, the design participants were presented with relatively small-scale design briefs based around core sets of requirements that may well have triggered co-evolution episodes by virtue of the constrained nature of the problem specifications and associated information. To some extent we can perhaps see this arising in the Dorst and Cross study, where all designers co-evolve novel solution ideas for a product that could keep newspapers separate to other items of litter, with this insight being triggered by cues arising in the given information sheets. Insofar as the constraints in the design brief may have primed the designers into similar solution paths leading to the forming of co-evolution bridges, it becomes important to examine whether and to what extent such bridging also occurs in less controlled environments. What would, therefore, seem to be particularly important by way of generalising a behavioural model of problem–solution co-evolution in design would be to examine design activity in an ecologically valid setting over a longer time-course.

To this end, the study that we report here examined *real-world* design data that derived from team-based product design and development meetings, with our aim being to identify and understand the co-evolution episodes that arise in professional design practice. One particular objective of this research was to derive further insights concerning the *directionality* of co-evolution activity in terms of whether it primarily involves movements from the problem space to the solution space or vice versa. Determining the nature and frequency of the occurrence of such different flavours of co-evolution episodes, such as those progressing from problem-to-solution or from solution-to-problem, is, in our view, of vital importance for gaining a comprehensive understanding of the role of co-evolution in creative design cognition. A further, important aspect of our analysis was to examine the way in which design co-evolution arises within a *team* context, where multiple collaborators work together to determine collectively a final design solution. Such a team-based focus sets our study apart from previous research on co-evolution in design, which has only examined the reasoning processes of lone designers.

In sum, our research aimed to address three broad questions, which, in turn, gave rise to a number of more specific, testable predictions. The first question was to establish whether co-evolution arises in naturally-occurring collaborative design activity. Our working assumption was that co-evolution episodes would feature strongly in real-world product design meetings and would play a particularly vital role in promoting the transition from an understanding of design requirements to the generation of solution possibilities. We likewise expected to see instances of co-evolution progressing in the opposite direction, with solution ideas evoking changes to design requirements and the potential addition of new requirements.

A second, related question concerned the way in which co-evolution arises in a team context. More specifically, does co-evolution arise in collaborative design in a similar manner to that observed in individual design activity? In this respect we predicted that co-evolution episodes would take two forms: first, episodes involving the design activity of a single designer, such as might arise when an individual suggests a modification for a design requirement and then explicates to the team how this might impact on solution ideas, and second, episodes involving two or more team-members where, say, various solution possibilities are suggested by different designers, or where one designer suggests a requirement change and another designer responds by proposing a novel solution attempt linked to the requirement change.

The third question that we wished to address concerned the way in which co-evolution might link to other creative cognitive processes that are known to arise in design. In this respect we were especially interested in pinpointing the association between co-evolution episodes and occurrences of analogical reasoning (e.g., Ball & Christensen, 2009; Ball et al., 2004; Christensen, 2010; Christensen & Schunn, 2007) and mental simulation (e.g., Ball & Christensen, 2009; Ball, Onarheim, & Christensen, 2010; Christensen & Schunn, 2008, 2009). Analogising and mental simulation are two creative design strategies that have been shown to be critical for overcoming moments of 'epistemic uncertainty' associated with an ongoing design project (i.e., when designers are unsure about how to proceed based on their current state of knowledge) and for facilitating problem understanding and solution generation in expert design reasoning (e.g., Ahmed & Christensen, 2009). We therefore predicted that there would be a strong alignment between co-evolution episodes and occurrences of analogising and mental simulation such that these creative processes would be seen to be at high levels *within* co-evolution episodes but at lower levels outside of co-evolution episodes.

The links that we assume should exist between analogising, mental simulation and problem—solution co-evolution give rise to risky experimental predictions (to be reviewed below) that could readily be falsified. Finding support for these predictions would, therefore, provide strong grounds for viewing co-evolution episodes as the 'engine' of creativity in design, with such creativity arising during the formation of bridging links between the problem space and the solution space (cf. Dorst & Cross, 2001). In relation to analogising, we note that analogies can serve multiple functions, being evoked for problem understanding, for solution generation, or for both activities (Ball & Christensen, 2009; Ball et al., 2004; Bearman, Ball, & Ormerod, 2007; Christensen & Schunn, 2007). We therefore generated an open-ended prediction in relation to the association between analogising and co-evolution since there are no a priori grounds for assuming that it might dominate either problem analysis or solution generation.

In relation to mental simulation, however, the existing evidence suggests that such simulation is primarily applied by designers as an evaluation strategy, whereby they engage in 'what if' cause-effect reasoning to determine the efficacy of solution possibilities (e.g., Ball & Christensen, 2009; Ball et al., 2010; Christensen & Schunn, 2009). As such we were able to make a theory-driven prediction that mental simulation would tend to dominate during the solution generation stage of any co-evolution episode rather than during the problem interpretation stage. We finally note that the previous evidence for strong links between expressions of epistemic uncertainty in design and the creative processes of analogising and simulation should likewise emerge in the present analysis in the form of epistemic uncertainty being at higher levels within co-evolution episodes than outside of such episodes.

## 4 Methods

The present study involved re-examining a set of verbal transcripts that had previously been collected in a study of analogical thinking in expert design (Christensen & Schunn, 2007; Christensen, 2005). The original data had been collected using Dunbar's 'in vivo' methodology (see Dunbar, 1995, 1997; Dunbar & Blanchette, 2001), which involves studying expertise 'online' in the form in which it arises in its natural context. In addition, the in vivo methodology involves taking a particular stance on data analysis, in that verbal data (including data deriving from team discussions) are coded using a similar approach to that deployed in the analysis of concurrent think-aloud protocols (e.g., Ericsson & Simon, 1993).

Christensen and Schunn's (2007) dataset consisted of audio and video recordings captured at a major international company that specialised in engineering design in the domain of medical plastics. The design project in question spanned 2 years and involved 19 expert engineering designers who were organised into smaller, cross-functional units or 'subgroups', each focussing on separate parts of the overall design. The aim of the project that was studied was for the designers to come up with a new and improved version of a product in a domain where the company holds multiple product patents and has extensive experience. The type of designing involved in this particular project can best be characterized as product design.

The particular focus of analysis for the present study revolved around the various product development meetings held by subgroups. In each subgroup the designers met on a regular basis (typically weekly) to progress the product design. This meant that the product development meetings were concerned with collaborative creating and therefore typically involved activities such as brainstorming, problem solving, planning data collection, evaluating mock-ups and prototypes, sketching, and concept development. Given the collaborative nature of these meetings, the designers were constantly talking aloud, thereby providing a rich, ongoing, external record of their thinking and reasoning.

One particular subgroup formed the focus for the present analysis, that is, the subgroup charged with the task of developing 'new features' for the product design during the concept-generation phase of the project, which arose over the first 5 months. The team consisted of 5 core members (1 female, 4 male) with extensive experience (from 10 to 35 years) representing different functional roles (e.g., industrial designer, lab technician, project manager) as well as different discipline backgrounds (e.g., machine engineering, architecture, machinist). In order to protect the company's intellectual property rights as well as the anonymity of the participants in the design team, further details of the exact content of the design brief and of the background of the designers cannot be disclosed. Occasionally, additional experts would sit in on team meetings that were related to their own areas of expertise.

During meetings the designers would normally work on several different design concepts, although usually two or three concepts would form the main focus of the session. The subgroup's product development meetings were video-taped using a single camera that captured the design objects present on the table between the designers as well as any associated object handling that took place. No special instructions to think-aloud were given, and the designers were merely asked to continue with the meetings as they normally would. The second author was present during the meetings, purely as an observer. The meetings lasted between 30 min and 2 h. The recordings were transcribed and segmented according to units of complete thought. A total of 7 transcripts covering approximately 9 h of video were used in the present data analysis, yielding a total of 7414 segments.

## 4.1 Protocol coding

The transcripts were initially reduced by coding for off-task behaviours (e.g., jokes, banter between the designers, office gossip or conversation of events unrelated to design) and for episodes dealing with summarising past meetings or planning future meetings or data collection. This data-reduction removed a total of 1602 segments. Next, the transcripts were coded for requirement mentions, solution attempts, analogising, mental simulation, and the presence of epistemic uncertainty. Requirement mentions, solution attempts, and co-evolution episodes were coded by an independent researcher who had received training both in protocol analysis and in this coding scheme using spare sections of the wider dataset. Analogising, mental simulation and epistemic uncertainty were coded by the second author.

Coding for requirement mentions involved examining each segment to determine whether it contained an explicit reference to a design requirement and whether this requirement mention involved: (a) adding a novel requirement; (b) interpreting or making revisions to an existing requirement; (c) bracketing a requirement (as in 'we're not going to be dealing with that here'); or (d) deleting a requirement. Each segment was further coded for whether the designers suggested a solution or idea in order to fulfil the design requirements (i.e., a solution attempt). Both solution attempts and requirement mentions typically spanned several segments. Finally, co-evolution episodes were coded by linking requirement mentions to solution attempts and by looking qualitatively at the content of each. Insofar as a requirement mention was categorised as being linked to a solution attempt within a 5-min transcript window, this was coded as being a 'co-evolution episode'.

All segments were coded for analogising using the method developed by Dunbar (1995, 1997), and previously applied in a design context by Christensen and Schunn (2007) and Ball and Christensen (2009). That is, a segment was coded as involving an analogy when a designer referred to another base of knowledge to explain, create, modify or evaluate a design.

Coding for mental simulation was adapted from Trickett and Trafton's (2007) coding scheme that was applied in a study that examined scientists running mental models during data analysis, and previously applied in a design context by Christensen and Schunn (2009). A mental model run is a mentally constructed model of a situation, phenomenon or object that can be grounded in memory or in a mental modification of the design objects that are currently present. Centrally, a mental simulation involves a simulation 'run' that alters an initial representation to produce a change of state (Trickett & Trafton, 2007). Mental simulations thus represent a specific sequence starting with creating an initial representation, running the representation (involving configural transformation, where elements or functions are extended, added or deleted), followed lastly by a changed representation. These three elements (initial representation, run, and changed representation) are not mutually exclusive and may occur in the same segment, although frequently they will cover several segments (see also Ball & Christensen, 2009).

Finally, a code of epistemic uncertainty was added in order to estimate the degree of epistemic uncertainty in the design dialogue. This was coded using a purely syntactical approach (Christensen & Schunn, 2009; Trickett, Trafton, Saner, & Schunn, 2007), whereby 'hedge words' that are linked to epistemic uncertainty were located, such as 'maybe', possibly', 'guess', 'don't know', 'believe' and so on. Then, for each hedge word, a qualitative screening was carried out ensuring that the hedge word, used in that context, did in fact display epistemic uncertainty (e.g., as opposed to being a politeness marker).

# 5 Results

## 5.1 Inter-rater reliability

Reliability checks for the codes were conducted on approximately 10% of the data, either by one of the authors (in the case of the independent coder doing the first pass), or by the independent coder (in the case where the second author coded the first pass). A kappa coefficient of inter-coder reliability was calculated for each code (see Table 1) and in all cases the reliability was deemed to be good.

### 5.2 Frequency of co-evolution episodes

The designers referred to requirements a total of 137 times (mean length of each mention 3.7 segments, ranging from 1 to 21), of which 47 were categorised as adding a novel requirement, 86 as interpreting or changing existing requirements, 3 as bracketing requirements, and 1 as deleting requirements. They made a total of 112 solution attempts (mean length of each mention 8.3 segments, ranging from 1 to 31). On 63 occasions, the requirements were linked to solution attempts both temporally and content-wise, thus creating a 'co-evolution episode'. The co-evolution episodes covered a total of 1009 segments, corresponding to 13.6% of the transcripts, showing that co-evolution episodes were common. Each co-evolution episode lasted 16.0 segments on average, ranging from 2 to 83 segments.

### 5.3 Collaboration and co-evolution episodes

Given that problem−solution co-evolution has not previously been investigated in a team context, we examined whether the episodes that we identified were collaborative (i.e., the requirement was mentioned by a team member other than the one who proposed the linked solution attempt), or individual (i.e., both the requirement change and solution attempt were proposed by the same individual). Amongst the 63 identified episodes 42 (67%) were collaborative, indicating that in a group context, the problem−solution co-evolution is indeed most often collaborative in nature. What this also implies is that the link that is created between a requirement being addressed and a solution being attempted is often not anticipated at the time of dealing with the requirement, but instead happens in an emergent manner as a result of the ongoing design dialogue. As such, not only are many problem−solution co-evolution episodes collaborative, but they are also distributed over time as opposed to arising as single requirement-solution 'leaps'. Nevertheless, it is important also to note that individual co-evolution episodes do arise as well and are not that uncommon (33%). Furthermore, the methodology employed in this study (i.e., the analysis of verbalizations in teams) may significantly

**Table 1 Kappa coefficients for inter-coder reliability**

| *Code* | *Kappa* |
|---|---|
| Solution attempt | .82 |
| Requirement mention | .67 |
| Requirement type | .66 |
| Co-evolution episodes | .90 |
| Mental simulation | .90 |
| Analogy | .71 |
| Epistemic uncertainty | .95 |

**Extract 1 An example of collaboratively forming a 'problem—solution' combination — Co-evolution episode 28**

| *Seg.* | *Designer* | |
|---|---|---|
| 424 | T | The best thing for a treatment plant is if this thing drops to the bottom |
| […] 427 | T | and the second best thing is if it can't get through the grate. |
| 428 | K | If you could get it …like when it gets wet, to stick together. So it does not get filled with air. |
| […] 442 | O | Yes, because it will … it just needs to stay intact for a quarter of an hour or something … half an hour and no more. |
| 445 | K | It should just stay intact a couple of minutes. It must be able to stick together … there's no point if it starts to leak. |
| 446 | L | I would say if we say half an hour, then that will probably be optimal so the user has a little time to stand and fumble about … |

underestimate the occurrence of individual co-evolution episodes, in that any silent (i.e., unspoken) individual episodes are clearly not available for recording and subsequent identification and tallying.

The co-evolution episodes shown in Extracts 1 and 2 provide examples of where at least four speakers were involved and where two or more iterations of problem—solution mentions can be observed. In Extract 1 (Co-evolution Episode 28) the team discusses the requirements for the disposability of the bag. The episode starts off with T pointing out two desirable behaviours of bags in a water treatment plant. K then comes up with a solution suggestion ("stick together when it gets wet") that is elaborated on by O and L regarding a durability requirement ("stay intact for a quarter/half an hour"). The extract provides an example of how the four team-members collaboratively form a 'problem—solution' pairing.

Extract 2 (Co-evolution Episode 42) involves a collaborative exploration of potential solutions concerning the requirement "less splashing while emptying

**Extract 2 An example of collaborative exploration of solutions for a specific requirement — Co-evolution episode 42**

| *Seg.* | *Designer* | |
|---|---|---|
| 70 | K | If we start from the little feedback we already have from the users, uhh then we can say that the only concrete thing we know that we should work on, that's this one … a bag for use in emptying. |
| 71 | K | Because we had feedback from the user forum, and we've also heard it … from our own … |
| 73 | K | They would like a bigger bag … |
| 75 | L | And then they said it was too narrow … and so I do not know whether we should … or perhaps you should have the welding weld all the way up. |
| 76 | L | Down there where it is welded together, there's simply too little space. |
| 77 | K | Yes, if you have to have the outlet all the way down here. |
| 78—80 | O | I think if we *extend the diameter* here. I reckon we should also *expand it* a little in … and then maybe *weld it higher*… further up … |
| 81 | L | Then there is the potential for… |
| 82 | M | Then we're probably just talking about scaling. Scaled up a bit. |
| 83 | L | Well I think you are right. |
| 84 | K | What I've written … what's it called here … ah yes it is called 'less splashing during discharge'. |
| 85 | O | No, you should be careful it cannot be too big here, because then it will look … then it's going to look awful. |

the bag", with four team-members participating in the episode. K starts off by citing user feedback, L responds by describing the problems with a current prototype, O hints at potential solutions ("expand diameter", "weld higher up"), summarised by M to "scale up a bit", before K makes a summarising requirement statement that is seconded by O and L.

## 5.4 Direction of co-evolution episodes

Although much interest in problem–solution co-evolution in design has tended to focus on requirements leading to solution attempts, it is equally possible that solution attempts spark off the analysis of requirements and possible changes to those requirements (cf. Dorst & Cross, 2001). This could happen, for example, if a solution attempt indicates potential avenues of promise in terms of augmenting specific aspects of the problem space. In the present transcript the most frequent type of co-evolution was in the requirement to solution attempt direction (47, or 75%), but in 12 cases (19%) the opposite directionality could be detected, and in 4 cases (6%), the directionality could not be discerned given that the requirement mention and the solution attempt started in the same segment.

In Extracts 3 to 6 we present qualitative examinations of some of the co-evolution-episodes that illustrate solution attempts leading to requirement changes. Extract 3 (Co-evolution Episode 6) is an example of a solution suggestion being introduced for the first time that leads to a new requirement statement being written down, and is followed by another solution suggestion linked to the related requirement. It opens with a suggested solution for the outlet "so that it opens itself". This leads to formulating and writing down the related requirement "increased hygiene" through "improved cleaning of the bottom flap", which is followed by mentioning the "injection-moulded" production technique as a potential solution path.

Extract 4 (Co-evolution Episode 63) is an example of where a solution suggestion and various requirements are closely related. It starts out with a suggested

**Extract 3 An example of noting a new requirement based on a solution idea – Co-evolution episode 6**

| *Seg.* | *Designer* | |
|---|---|---|
| 201 | L | … Could we make it so that it opens itself … so you do not actually need to go down and fiddle with the flap here. |
| 202 | K | Well there are some people who want to … |
| 203 | M | There are some people who want to bend the flap over backwards. |
| 204 | L | Yes … backwards… perhaps we should have a look at the hygiene around this flap. |
| 208 | K | Yes, but here we can write uhh … |
| 209 | L | Yes increased hygiene on uhh |
| 210 | K | improvements … improved cleaning of the bottom flap or what? |
| 211 | O | There uh there an injection-moulded solution is again a good idea because it will be easier to wipe clean. |

**Extract 4 An example of a solution attempt with three related requirements − Co-evolution episode 63**

| *Seg.* | *Designer* | |
|---|---|---|
| 390 | K | It's no good we place them so far down that they do not have any effect. |
| 391 | L | Well, I think to some extent that we should try to find the mechanical functions we want in the bag … |
| 392 | O | Yes |
| 393 | L | and then only let ourselves be limited by mechanics afterwards. |
| 394 | K | But it has to be *able to flow down*. |
| 396 | K | And it should still be able to *hang neatly* - otherwise there is no point in … |
| 398 | O | Also, we must find out whether you can *empty the bag*. If you cannot, then the whole thing does not matter. |

location (not too far down) for elements of the outlet part, which is followed by a suggestion for the process of deriving and working out the requirements that need to be fulfilled simultaneously. Two colleagues point out the requirements that need to be considered ("ability to flow down", "hang neatly", "possibility to empty the bag").

Extract 5 (Co-evolution Episode 66) represents an example of an episode where a novel solution approach is suggested that subsequently gets turned down after an evaluation of the related requirements. The episode starts off with the enquiry as to whether anybody has tried to weld all layers of the bag together with the adhesive in one go. The implications of this suggestion are discussed in terms of production techniques and the visual appearance of the bag. The episode continues with another back-and-forth transition

**Extract 5 An example of turning down a novel solution suggestion after exploration of requirements and the return to a previous solution − Co-evolution episode 66**

| *Seg.* | *Designer* | |
|---|---|---|
| 630 | L | … Now I'll ask a stupid question… has anybody ever toyed with the idea of welding uhh all foil layers in one go? |
| 631 | K | Yes on there, yes. The problem is the adhesive. |
| 632 | O | Welding what you say? |
| 633 | L | Weld adhesive and all of it together here in one go |
| 634 | K | From the front? |
| 635 | L | Yes from the front |
| 636 | K | Through all of the layers … in the beginning, there was … |
| 637 | L | where you make a contour welding onto the adhesive |
| 638 | O | I don't think anybody has ever tried … |
| 639 | K | The limitation is that you … I do not think you dare … produce bags that are made that way |
| 640 | O | I actually think that the adhesive will look like crap. |
| 642 | K | Well, we've never really tried to work with the adhesive part. They've tried playing with the idea of doing something with putting non-woven on top of it, making it look nicer. So it becomes more patch-like … |
| 644 | O | Yes but if you go down and pressurize with heat here, and then you take the heater off, then you'd be able to see … |
| 645 | L | Yes you would be able to see it. |
| 646 | O | I think that would basically destroy it. |
| 647 | L | Okay, well it was just a thought I had … |

**Extract 6 An example of a chain of transitions from solution to requirements to solution and back to requirements − Co-evolution episode 23**

| *Seg.* | *Designer* | |
|---|---|---|
| 1084 | K | Zipper closure, we have worked on that. The … when we made this one. And it is so difficult. Something easily gets into the zipper, and then … how do you stop it? |
| 1087 | K | You have to open it up and … it does not open by itself. You have to pull it apart …you can make a wall in the zipper of course … |
| […] 1099 | K | So it must be a zipper that closes by itself right. |
| […] 1107 | M | It should not be a 'must' that you have to hold it down like this to activate it because it will annoy many of our faithful users uh … |
| 1109 | G | Well then we should maybe differentiate thickness … here … so it gets thinner in the middle or something … |
| […] 1113 | M | So that we could put something [spray] or something in when we work with injection-moulded … we cannot do it with foam … but we cannot risk … when you have just let go of the lower flap then it comes all by itself … |
| 1114 | K | And here we have the "dumb proof" again … self-explanatory |

between discussion of the solution idea and consideration of the designers' previous experience with factors that might prevent the solution from working. After the presented segments the designers conclude the episode with a reference back to a solution using Velcro, which successfully resolves the issue.

This episode in Extract 6 (Co-evolution Episode 23) starts with the re-iteration of a solution concept (the "zipper solution") that had received some attention previously. The discussion of requirements revolves around differentiation in terms of thickness of material and production method (injection-moulded not foam). In a second step the overall solution suggestion is considered in relation to the "dumb proof/self-explanatory" requirement.

In summary, while most of the problem−solution co-evolution episodes started off with an analysis of a requirement that was then followed by one or more solution attempts, this directionality was not always the case, and there were occasions when solution attempts engendered requirements analysis and requirement changes. In addition, qualitative analyses of individual co-evolution episodes revealed that many of the initial requirement changes that led to solution attempts seemed to be pre-planned, being purposefully introduced by the team leader. In other words, many design conversations were observed to commence with the team leader mentioning or slightly amending a design requirement, which was subsequently followed by solution attempts. An example of co-evolution initiated by the team leader can be seen in Extract 7, where they introduce into the conversation the idea that it is possible to add a requirement relating to the prevention of certain types of misuse of the product.

The team leader's final comment in Extract 7 concerning the impossibility of introducing such a requirement does not, however, prohibit the team from

**Extract 7 : An example of a co-evolution episode that was initiated by the team leader, who identified the possibility of a new design requirement − Co-evolution episode 55**

| *Seg.* | *Designer* | |
|---|---|---|
| 48 | K | What else have we got … then we've talked about whether we could do something to avoid … making it impossible to fold it this way. But that's a problem for |
| 49 | M | … the ones who'd like to. |
| | | Yes, it's a problem for those who want to fold it that way while emptying. If you could make something so it was not so high up. |
| 50−53 | K | … so you couldn't fold it if … but that's completely impossible. |

pursuing a string of solution suggestions over the next few minutes involving structurally changing the product in several distinct ways, such as incorporating colour coding, adding text or changing the user instruction manual. These episodes did not seem to involve great leaps in creative discovery regarding how the formulation of the problem should change, but rather entailed minor increments being introduced by the team leader in order to change the focus to another part of the design problem space. As such, many co-evolution episodes revolve around fairly ordinary design dialogue concerning relatively minor requirement changes, rather than unique design dialogue aimed at driving major shifts in the understanding of what the problem space entails. Indeed, the introduction of requirement mentions into the design conversation seems simply to be geared towards ensuring the effective conceptual decomposition of the overall design problem into its component parts, with requirement mentions then serving to direct the attention of the designers in a particular direction, resulting in solution attempts aimed at a specific part of problem space.

### 5.5 Individual co-evolution episodes

Co-evolution episodes where one of the designers reasons about an episode independent of the involvement of other team-members closely resemble concurrent verbalisations arising in think-aloud protocols. Nevertheless, the attentive listening by colleagues might not truly resemble the "neutral observer" position that researchers tend to emulate when conducting their laboratory studies via think-aloud protocols. Extract 8 (Co-evolution Episode 17) contains an

**Extract 8 An example of an individual co-evolution episode − Co-evolution episode 17**

| *Seg.* | *Designer* | |
|---|---|---|
| 697 | K | "Avoid mess on fingers," and there is also that one "avoid splashing," which we have talked about. "Avoid mess on fingers," that also means easier to clean. The fewer times they have to wipe, the less likely it is that they get it on their fingers. |
| 698 | L | Certainly, but it is also a question of handling it now that they have to open it and … |
| 707 | K | But could we imagine … now I know we have a patent on that flap, and it actually closes …, but we could imagine we could close it in another way than with this big flap? |
| 708 | K | Where you just … click … Where you just have a little narrow line here, right? |
| 709 | L | A clamp … |
| 712 | K | You empty it, then you wipe once, and close it, and then you fold it up. |
| 713 | L | A little ala those with a zip. With a zipper |

example of an individual co-evolution episode, with K picking up two requirements and starting to reason herself about potential solutions related to them. L is an affirmative listener in the conversation but K is more-or-less "thinking aloud" for herself. This episode also contains one of the observed analogies ("Zipper").

### 5.6 Epistemic uncertainty and co-evolution episodes

Segments that were not associated with co-evolution episodes contained linguistic markers of epistemic uncertainty in 4.8% of cases, which is regarded as providing a baseline measure of uncertainty for the transcripts. In comparison, for segments that were associated with co-evolution episodes, 8.6% reflected epistemic uncertainty, differing significantly from baseline, $t(62) = 2.72$, $p < .01$. Segments within co-evolution episodes that involved requirement analysis (i.e., segments associated with exploration of the problem space) did not differ significantly from baseline in terms of epistemic uncertainty, $t(62) = 1.70$, ns. However, segments within co-evolution episodes that concerned solution attempts (i.e., segments associated with exploration of the solution space) did differ significantly from baseline in epistemic uncertainty, $t(62) = 3.20$, $p < .003$.

This latter finding indicates that it is the solution-attempt aspect of co-evolution episodes that elevates uncertainty levels above the baseline value. Extract 9 is an example of part of a co-evolution episode that illustrates the cautious introduction and exploration of potential solution pathways and the resulting choices concerning related requirements. Interestingly, too, both the solution suggestions and the requirement statements are questioned immediately by the person who is uttering them. In the following subsection we focus our analysis more closely on co-evolution episodes where expressions of epistemic uncertainty were present in problem-related and solution-related segments.

#### 5.6.1 Requirement types

Requirement analysis frequently led to co-evolution episodes. Indeed, 28% of segments within episodes involved requirement analysis, whereas only 3% of

**Extract 9 An example of the cautious introduction of potential solution pathways − Co-evolution episode 2**

| *Seg.* | *Designer* | |
|---|---|---|
| 72 | O | What I also would like to do, it was like to try the hard one up here, with the soft plastic moulded down there |
| 74 | O | But I ***don't think*** that is going to get us anywhere … |
| 75, 76 | O | I ***don't think*** so, because when this thing cannot beat that − then I ***don't think*** the soft one can either. |
| 77 | K | But then the question have to be…… how should we proceed … should we proceed with an injection-moulded on the top part, and keep the foam solution, or … should we cast an even softer version… but that's not a good solution − I don't ***believe*** that. |

segments outside of episodes involved requirement analysis, $\chi^2(1) = 833$ (Yates), $p < .001$, indicating a very close link between requirement analysis and co-evolution episodes. Furthermore, it was evident that requirement analysis involving epistemic uncertainty was more likely to arise within co-evolution episodes than outside of co-evolution episodes, $\chi^2(1) = 4.88$, $p < .03$ (see Table 2). This indicates that the designers were frequently seeking to generate solution attempts following uncertain requirement analysis. This is a finding that supports the theoretical account proposed by Ball et al. (2010), whereby expert designers are viewed as primarily utilizing a breadth-first solution development strategy, but with episodes of depth-first solution exploration arising that are triggered by highly complex and epistemically uncertain requirements and constraints.

Given previous research interest in different types of requirement change (e.g., Maher, 1994; Maher & Poon, 1996), we examined whether different requirement types had distinct consequences on the length of co-evolution episodes (arguably a measure of the interest raised by the requirement), or the level of epistemic uncertainty within the episodes. As noted previously, requirements were coded as being of four types: (a) adding a novel requirement; (b) interpreting or making revisions to an existing requirement; (c) bracketing a requirement (as in 'we're not going to be dealing with that here'); and (d) deleting a requirement. It was found that requirement types did not vary significantly in term of the length of episodes, $t(59) = .75$, ns, nor were there any differences in the levels of epistemic of uncertainty associated with different requirement types, $t(59) = 1.28$, ns. The different requirement types were also distributed equally within episodes and outside episodes, $\chi^2(3) = 4.89$, ns.

## 5.7 Solution attempts and co-evolution episodes

Most of the solution attempts (84%) happened within co-evolution episodes. Indeed, 75% of all segments within co-evolution episodes revolved around solution attempts, whereas only 2% of segments outside of co-evolution episodes involved solution attempts, $\chi^2(1) = 4261$, $p < .001$. This provides very strong evidence of the close link between co-evolution episodes and solution generation in the present dataset and attests to the importance of problem–solution co-evolution in design.

## 5.8 Mental simulation and co-evolution episodes

Mental simulations tended to co-occur with co-evolution episodes. Indeed 45.5% of segments within co-evolution episodes involved mental simulation,

**Table 2 Number of requirement analyses inside and outside of co-evolution episodes that were associated with the presence versus the absence of uncertainty**

| *Location of requirement analysis* | *Uncertainty absent* | *Uncertainty present* |
|---|---|---|
| Outside co-evolution episode | 61 | 7 |
| Inside co-evolution episode | 52 | 17 |

whereas only 11.4% of segments outside of co-evolution episodes involved mental simulation, $\chi^2(1) = 751.12$ (Yates), $p < .001$. In addition, for those co-evolution episodes that involved requirements analysis leading to solution attempts, the mental simulation activity was closely associated with the solution attempt segments of the episodes (i.e., arising in 56.5% of segments relating to solutions), with correspondingly less mental simulation taking place in requirement analysis segments (i.e., 24.4%), $\chi^2(1) = 67.0$, $p < .001$.

In Extract 10 we present an example of a mental simulation being run by a single designer. In this extract, L simulates for himself and his colleagues how his solution suggestion might apply and how the bag would be located on a user's body.

In Extract 11 we give an example of a 'collaborative' simulation that was run by two colleagues. In this extract O is simulating a colour-code solution for the outlet. It seems he is not very convinced himself as to whether this is a good idea and K builds on O's musings and continues to take the simulation forward.

## 5.9 Analogical reasoning and co-evolution episodes

As with simulation, analogical reasoning also seems to co-occur with co-evolution episodes. Indeed 2.9% of segments within co-evolution episodes involved analogical reasoning, whereas only 1.3% of segments outside of co-evolution episodes involved analogical reasoning, $\chi^2(1) = 13.55$ (Yates), $p < .001$. Furthermore, in co-evolution episodes where the analysis of a requirement led to a solution attempt, analogical reasoning was closely associated with the solution attempt part of the episodes (i.e., analogical reasoning arose in 4.1% of segments relating to solutions), with less analogical reasoning taking place in requirement analysis segments (i.e., less than 1%), $\chi^2(1) = 5.79$, $p < .02$.

Given that neither analogising nor mental simulation occurred more frequently than baseline levels in the requirement analysis parts of co-evolution

**Extract 10 An example of a mental simulation run by one individual − a part of Co-Evolution episode 40**

| *Seg.* | *Sim* | *Designer* | |
|---|---|---|---|
| 520 | 1 | L | If we use the time to […] empty it. So that u … what's it called … it's sitting here with the bag folded up and closed. […]. So you insert the slide here and as you open it, you fold it around. Like this. Then it sticks to the back of the slide. |
| 521 | 1 | L | And then you have better control … the bag is lying down in front of you … so you can better control. At the same time you have the second flap also lying down… then you can pull up the other flap and lock it to these two and then … without getting any dirt on your fingers. |
| 522 | | K | Does the outlet stop here? |

**Extract 11 An example of a collaborative mental simulation – a part of Co-evolution episode 56**

| *Seg.* | *Sim* | *Designer* | |
|---|---|---|---|
| 116 | 1 | O | No it can't, but if you could colorize this side, and match the colour up here … |
| | 1 | O | so it looked like a coherent colourpiece when you closed it like this. |
| 118 | 1 | O | But uhh I'm not even sure that it going to work |
| 119 | 1 | K | Then it should have a different colour on this side that absolutely does not match the other one. |
| 121 | 1 | K | That would create a contrast between this and that. |
| 122 | 1 | K | But we'll see … if we are going to be working with a larger plate then we're also going to be seeing more of the backside … |

episodes that involved requirements leading to solution attempts, the present analysis cannot point to a specific form of creative process, whether analogising or simulation, that engenders requirement changes. As such, our quantitative analysis does not support the argument that analogising or mental simulation are the 'drivers' of co-evolution episodes. Rather, these creative processes are contained mainly in the solution attempt part of co-evolution episodes. The qualitative analysis also hints at the possible intentional use of requirement changes by the designers, in that it would seem that the team leader was purposefully exploring various parts of the problem space by introducing minor requirement changes into the design dialogue, after which the conversation revolved around these. Such a planned and purposeful utilisation of requirement changes seems to point to co-evolution episodes as involving 'design-as-usual' and arising from the natural design dialogue, rather than in some way revolving around special or out-of-the-ordinary processes alongside phenomena such as 'insight' or 'aha-experiences'.

## 6 General discussion

The present study aimed to examine the validity of a problem–solution co-evolution model of design behaviour as espoused by Dorst and Cross (2001) and Maher and Tang (2003). In pursuing this goal we were keen to take the analysis of co-evolution outside of a laboratory context and focus instead on team design processes arising in real-world design practice, where collaborating designers work on the development of innovative concepts to meet the commercial goals of a company, which, in our study, was a world-leading producer in the domain of medical plastics.

A pivotal question that was driving our analysis was to establish whether co-evolution does indeed arise in such naturally-occurring collaborative design activity. The answer to this question was a resounding 'yes', with no less than 63 co-evolution episodes being identified, with each revealing requirements that were associated with the problem space being intimately linked with solution generation activity arising within a 5-min transcript window. We note that although we employed this '5-min rule' as a simplifying assumption to allow us to delimit co-evolution episodes, it nevertheless provided us with a highly principled way to extract such episodes from the midst of the complex dynamics of each design transcript.

The 63 co-evolution episodes that we identified made up a relatively small − but nonetheless non-trivial − proportion of the overall transcripts (i.e., 13.6% of transcript segments), indicating that co-evolution was certainly an important aspect of collaborative design. In addition, we observed co-design episodes that embodied a variety of directional movements between the problem space and the solution space, and although co-evolution activity was dominated by requirements analysis leading to solution attempts (i.e., 75% of co-evolution episodes) there were also numerous instances where solution attempts sparked off requirements analysis (i.e., 19% of episodes), which often resulted in requirement changes. It is perhaps unsurprising that innovative design is so heavily dominated by co-evolution that moves from problems to solutions, given that this would be the expected direction of commercially-oriented design activity that is primarily focused on the generation and evaluation of solution possibilities for new products. However, the clear presence of co-evolution arising in the reverse direction − from solutions to problems − attests to the fundamentally bi-directional nature of co-evolution and its capacity to alter aspects of the problem space through processes whereby requirements are reinterpreted, amended, deleted and the like (cf. Maher & Tang, 2003). Occasionally, too, we observed that new requirements were introduced subsequent to solution generation activity, and we additionally witnessed some fairly complex co-evolution episodes that entailed cyclical iteration between requirements and solution ideas, which again supports the view that co-evolution is a sophisticated process that plays a vital role in driving forward design activity.

A second question that we wished to address in this research concerned the role of the design team in engendering co-evolution behaviour. In this respect we observed that 67% of co-evolution episodes were collaborative in nature, involving contributions from at least two members of the team. As such, team-based co-evolution dominated co-evolution activity, with designers feeding off one another's proposals when understanding and changing requirements and when generating and developing solution possibilities. One critical upshot of this dominance of *collaborative* co-evolution in design is that it underscores the truly *emergent* nature of design development, given that the designers could not easily predict in advance what their colleagues might add to the developing problem−solution framing.

We also observed that many design conversations were initiated by the team leader mentioning or amending a design requirement. Other members of the design team would then contribute useful ideas, either by way of developing the interpretation of the requirement or by way of generating and evaluating solution possibilities. The team leader seemed to be instrumental in sparking off co-evolution episodes in this way, ensuring that the design process continued to move forward in a manner that embodied both given and new design requirements. The role played by team leaders in collaborative design is often not remarked upon in many empirical studies of the design process, yet this role seems to be vital for the achievement of organisational goals relating to the delivery of high-quality, innovative design solutions that ensure a market lead. Such observations in the present study are resonant of evidence deriving from an ethnographic study of commercial design teams reported by Ball and Ormerod (2000a, 2000b), which showed how team managers deploy a wide range of tactics in team meetings to ensure that team effectiveness is maximised. Such tactics that were observed by Ball and Ormerod included team managers making regular conversational interjections aimed at avoiding premature commitment to initial solution concepts, ensuring that favoured concepts were appropriately challenged and evaluated, and facilitating breadth-first coverage of the full space of design requirements.

A third question that we addressed in the present research concerned the way in which co-evolution is linked to other creative processes that have been shown to arise in design, such as analogical reasoning and mental simulation (e.g., Ball & Christensen, 2009; Ball et al., 2004; Ball et al., 2010; Christensen & Schunn, 2007, 2009). We predicted that there would be a strong temporal alignment between co-evolution episodes and instances of analogising and mental simulation given that co-evolution episodes should reflect points in the design process where creativity is heightened as conceptual bridges are formed between the problem space and the solution space (see Dorst & Cross, 2001). This predicted relationship between co-evolution and creativity was fully supported by our findings. Mental simulation was seen to co-occur with co-evolution, with 45.5% of segments within co-evolution episodes involving simulation and only 11.4% of segments outside of co-evolution episodes involving simulation. Such simulation within co-evolution episodes was most closely associated with the generation of solution ideas, which is very much as we expected, since simulation in design is typically deployed as a means to evaluate the viability of solution ideas (e.g., Ball & Christensen, 2009; Ball et al., 2010; Christensen & Schunn, 2009).

As with mental simulation, analogical reasoning was also found to co-occur with co-evolution episodes, with 2.9% of segments within co-evolution episodes involving analogising, and only 1.3% of segments outside of co-evolution episodes involving analogising. In addition, and again in a similar manner to simulation, analogising dominated co-evolution segments that related to solution generation rather than requirement analysis. Taken together, the analogising and simulation data clearly support a view of co-evolution as being closely aligned with creative processes, with such processes being primarily directed towards idea generation and idea development within the solution space.

Our analysis of team design also attested to the predicted relationship between epistemic uncertainty and the occurrence of mental simulation, analogising and problem–solution co-evolution. Direct expressions of epistemic uncertainty were seen to be at relatively high levels (8.6% of segments) within co-evolution episodes but at comparatively low levels outside of co-evolution episodes (4.8% of segments). Moreover, the epistemic uncertainty arising within co-evolution episodes was mainly located in segments associated with the designers' exploration of the solution space. This finding concurs with the observation in the present study that mental simulation and analogising likewise arose primarily during solution exploration, given that we know from previous research that there are intimate ties between epistemic uncertainty and occurrences of analogising and simulation (Ball & Christensen, 2009; Ball et al., 2004; Ball et al., 2010; Christensen & Schunn, 2007, 2009). Notwithstanding the dominance of epistemic uncertainty in relation to design activity arising in the solution space, there were still occasions when epistemic uncertainty arose during requirements analysis as part of a co-evolution process, triggering solution generation activities that were presumably aimed at helping to resolve the uncertain requirements (see Ball et al., 2010. for related evidence of uncertain requirements triggering depth-first design development associated with extended simulation runs of solution possibilities).

Overall, we view our study as having advanced an understanding of problem–solution co-evolution in design by generalising the evidence of such co-evolution to a team-based design context involving collaboration and team management, and by revealing the close links between co-evolution and creative processes of analogising and mental stimulation. As we have noted, the evidence points to co-evolution episodes as being the creative engine of everyday design practice. This is not to belittle the importance of such creativity; although it may not have the characteristics of the 'aha' moments that typify more profound design insights, such everyday creativity is clearly central to much contemporary product design in commercial contexts. Our view of creativity in co-evolution therefore has a great deal in common with Dorst and Cross's (2001) position, where co-evolution is viewed not so much as promoting creative leaps as the building of bridges between the problem space and the solution space that allow problems to be framed in the form of linked problem–solution pairings.

Future research examining co-evolution behaviour in design would, we believe, do well to track in more detail the precise temporal aspects of the co-evolution process in company-based design contexts, perhaps with a more central focus on the role of the project manager. In our research our analysis of such manager input into co-evolution was assessed incidentally, rather than having been an a priori focus of our study. Yet even from our tangential analysis, it seemed clear than the manager was having a critical strategic influence on the team dynamics associated with co-evolution, in particular by introducing into the ongoing design dialogue various requirement interpretations and changes that would thence spark off solution-oriented dialogue.

As noted by Ball and Ormerod (2000a, 2000b) the team manager is often critical for design success in commercial contexts, and it would be valuable for future research to examine the full range of strategies that team managers deploy to advance effective co-evolution, including the possibility that they have tactics for recognising and facilitating emerging insights, thereby ensuring the fitness function between problem and solution spaces. Presumably, too, it is also team managers who implement effective stopping rules (Maher & Poon, 1996) in collaborative design contexts, so as to ensure the termination of activity that is focused on particular design requirements, thereby ensuring the attainment of an efficient commercial design process. The team design context is also interesting in that team-based team structures are often labile, with individuals possessing different types of expertise frequently moving in and out of teams on a regular basis. It would be interesting for future research to examine how such natural mutability of design teams influences co-evolution, either positively or negatively.

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