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ENHANCING THE CONCEPT GENERATION CAPABILITY OF NOVICE ENGINEERING DESIGNERS

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ABSTRACT

The professional contribution of an engineer often includes the generation of design concepts in response to an identified need. Concept generation creativity has multiple measures of interest, including: fluency, flexibility, originality and elaboration. Of these metrics, fluency measures the total number of concepts generated, and is of critical importance to an engineer's capability for concept generation. This work reports on a program to enhance the fluency of the concept generation capability of novice engineering designers. The program involves a novel computer based, self-assessed method to capture in real time the fluency of a novice engineer in response to a design task. The outcomes of this work can be applied to assess the effectiveness of teaching on fluency, and can provide tailored feedback to students to identify and overcome scenarios that may have negative influence on concept generation fluency. The outcomes of this initial work suggest that simple methods with minimal teaching overhead can be used to enhance concept generation capabilities. These outcomes are being used to inform a more extensive research program.

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1 INTRODUCTION

The ability to generate potential solutions to an identified need is of vital importance to the practicing engineer. By generating a comprehensive list of concepts, the designer mitigates the risk of failing to identify an optimal solution within the available development time and budget (Ulrich and Eppinger, 2008).

Despite the importance of comprehensive concept generation, there is little consensus on suitable methods to instill concept generation capabilities in the novice engineering designer. The production of plausible solutions to open-ended engineering problems requires an act of *creativity*, one of the *right-brain* skills that receive little attention in engineering courses (Field, 1995). Numerous researchers have explored ways in which successful designers appear to work, and have published various tools and aids to facilitate the creative process (de Bono, 1986); for example, *TRIZ* (Altshuler, 1984), *Brainstorming* (Osborne, 1953), *Classification charts* (Field 2011), *Abstraction* (Robertson, 2001), *Synectics* (Gordon, 1961). It has been traditional to teach novice designers some of these methods, and to encourage the use of those techniques during the formative stages of an engineer's professional development. These techniques generally encourage the generation of a greater number of concepts or to broaden existing concepts, but the subjective nature of creative activity makes it difficult to determine (i.e. measure) the success of such approaches (Adams, 2005).

2 FORMAL METHODS TO ENHANCE CREATIVITY

Methods have been proposed in the literature to enhance concept generation abilities. Some of these methods involve constructing a working environment that encourages natural creativity, such as the formal recognition and rewarding of creative achievements, and the reduction of mental "set" that channels thought in narrow paths (Adams, 2001). However, within undergraduate engineering courses, it is acknowledged that the majority of engineering students are predisposed to be type 2 or 3 learners (Kolb, 1984, Lumsdaine and Lumsdaine, 1995), which corresponds to a distinct preference for learning in structured, logical and piecemeal paradigms. Consequently, engineering students and their teachers typically embrace systematic methods for ideation, where a formulaic approach can be applied to the generation of concepts. Unfortunately, the literature does not report on the consistent success of any single "universal" concept generation tool, so it is up to individual design educators to present, and encourage the use of a range of methods that might be applied to different types of problem.

Within the context of the proposed Concept Generation Program initiative reported in this paper, the following strategies were identified to a class of undergraduate mechanical engineering students in a traditional lecture environment as possible methods to enhance the quality of concept generation outcomes. Fundamental theory was presented, as well as case studies illustrating feasible applications of each concept generation tool:

- ***Brainstorming:*** Brainstorming is a group method of idea generation developed with the intent of enhancing creativity (Osborn, 1953). Brainstorming allows for spontaneous ideas generation within a group with the following general rules: focus on quantity (fluency), withhold criticism, welcome unusual ideas, combine and improve ideas.
- ***Biotics:*** Design from nature allows for creative inspiration from the natural domain. Technical systems, which have been inspired by nature, include wing geometry for low speed flight inspired by owl wings, and the inspiration for temporary fasteners from plant burrs.
- ***Domain swapping:*** Domain swapping attempts to obtain inspiration from one technical domain for application to another domain. For example, industrial scrubbing technology applied to a bagless vacuum cleaner.
- ***Internal and External searches:*** The likelihood of fluent and flexible outcomes is enhanced by consciously eliciting input from sources internal to the design team; e.g. design team members and company resources; as well as external sources; e.g. product benchmarking and literature and patent searches.
- ***Synectics***: By reference to an extensive set of recorded meetings, Synectics attempts to identify a rational approach to problem solving, with the aim of enabling consensus of a group on a preferred concept for a design problem (Gordon, 1961). Synectics presents strategies to

overcome inhibitions to the generation of creative concepts, including, for using metaphor to "make the strange familiar and the familiar strange".

- ***Morphological analysis:*** The *Morphology Technique* is a well known method of generating a large number of concepts by firstly identifying the key aspects or functions of the solutions, then separately listing methods of fulfilling each of those functions (Wankel, 1965; Pahl and Beitz, 1984; Hubka et al., 1988). A solution concept is defined by selecting one method of fulfilling each function and then integrating those separate methods. The set of functions and their separate methods is typically displayed in a matrix to facilitate a systematic search through the plausible solutions.
- ***Abstraction:*** By making useful generalisations, the designer is freed of misconceived problem constraints and encouraged to focus on the fundamental problem needs (Robertson, 2001). Abstraction is particularly useful in overcoming obstacles to revolutionary design outcomes.

3 MEASURES OF CREATIVITY

The generation of concepts is at the core of problem solving and innovation. Due to the abstract nature of creative conceptualisation, it is difficult to assess the value of concepts generated by various individuals. Ongoing research programmes (for example, Shah et al, 2003, Field, 2011) attempt to measure correlated performance or psychological characteristics of recognised creative individuals, such as their spatial skill, their academic achievements, and their performance on a standardised set of controlled tests. Other researchers rely on the subjective opinions of a panel of experts to rank or rate creativity within a specific task domain (Yilmaz et al, 2010).

An extensive number of measures of creativity potential have been proposed (Adams, 2005). Of these, the most commonly applied measure of creativity is the Torrance Tests of Creative Thinking (TTCT) (Cropley, 2001; Piirto, 2004). The TTCT was originally proposed by Torrance in 1966, and subsequently updated (1974, 1984, 1990, 1998). Although the TTCT has received criticism, for example (Kim, 2006), it remains the most referenced of all creativity tests (Lissitz and Willhoft, 1985), and that in general, "creativity test scores are better predictors of creative life achievements than IQs or school grades" (Cropley, 2001).

The originally proposed TTCT consisted of the following measures, based on the divergent thinking factors proposed by Guilford (1959):

- Fluency – the ability to generate ***many*** ideas
- Flexibility – the ability to generate ***varied*** ideas
- Originality – the ability to generate ***unusual*** ideas
- Elaboration – the ability to ***add to*** existing ideas

More recent versions of TTCT include the following additional measures:

- Abstractness of Titles – the ability to extend beyond ***literal labeling*** of ideas
- Resistance to Premature Closure – the ability to keep an ***open mind***

Furthermore, the explicit measure of Flexibility is not included in recent versions of TTCT, due to an identified high correlation with fluency (Hebert et. al, 2002). This correlation is affirmed by Samuel and Weir (1999), "*fluent idea generators tend to be capable of generating many distinct ideas, while inflexible idea generators tend to be less fluent*".

All measures, with the exception of fluency and flexibility, suffer from a limitation of being laborious[1] and subjective in the method of scoring (Cropley, 2001). Although careful design of the test scenario can minimise systematic errors, only measures of fluency and flexibility are compatible with the time pressure associated with a typical engineering design course.

3.1 Measures of fluency and flexibility

Adams (2001) developed a one-dimensional problem solving activity to test for fluency and flexibility based on the application of a mundane object to a series of applications. For example, to expand market share, a manufacturer of red bricks has requested that as many as possible uses for red bricks be identified. A fluent concept generator may conceive a large number of building related applications (e.g. "build a house", "build a wall", "build a path"). A flexible concept generator will also identify non-obvious opportunities in alternate domains, for example, utilising the: mass properties (shipping

[1] TTCT is a trademark of Scholastic Testing Service. Certification of TTCT assessors is required due to the complexity of scoring (Bensenville, IL: Scholastic Testing Service, Inc.).

ballast, door stops), volume properties (concrete foundations, water displacement), abrasive properties (ground and included in paint for anti-slip finish), colour and texture properties. These non-traditional and non-obvious concepts provide an opportunity for innovation.

Fluency and flexibility are readily measurable without requiring specialist training, and are therefore compatible with the resource limitations associated with a typical engineering design course. These measures will be applied to a design problem of the type proposed by Adams (2001) to obtain some insight into the creative concept generation capability of novice designers. Furthermore, given that both fluency and flexibility are strongly correlated (and that flexibility does not exist in the current TTCT), only fluency will be measured directly.

4 MEASUREMENT METHOD

An experimental scenario was developed to quantify the designer's response to a concept generation task of the type proposed by Adams (2001) while minimising the risk of systemic error, and allowing a relatively large sample size within the available design time and budget.

A comparative study of alternative methods was completed to record concept generation attributes, including:

- *Audio recording*, where the concept generation task is recorded in an audio format, and transcribed by manual interrogation.
- *Video recording*, with similar attributes to audio recording but with an audio-visual file to be interrogated.
- *Direct observation*, where the important attributes of the process are documented in-situ by a trained observer.
- Computer based sampling, where the subjects interact with a computerised tool that manages the concept generation task and samples the subject response.

Of these methods, computer based sampling was identified as the preferred method (Leary and Burvill, 2005) for the work reported in this paper, as the required hardware (i.e. computer laboratories) is readily available, the novice engineer population being studied is computer literate and labour costs are be minimized (irrespective of the sample population size) due to University budget constraints.

A self-administered, computer based sampling tool was developed that allows programmable concept generation scenarios to be assessed in a repeatable manner. It is designed to enable rapid and efficient recording of ideas by a subject, so that it does not adversely impact the concept generation process. The sampling tool records a description of each generated solution (concept) proposal, and the time at which it was recorded. No attempt is made to evaluate or constrain the quality of a concept generated.

Advantageous features of the computer based sampling tool:

- The concept generation task is self-administered by the subject (designer).
- Direct observation of the subject is not precluded.
- The system allows a high "limiting rate" of data acquisition, that is, the sampling tool permits rapid recording of ideas, with minimal influence on the concept generation process.
- The system is highly flexible, and may be programmed to present a range of scenarios, limit the allowable concept generation time, and provide time-based cues to the subject.
- Provides in-situ analysis of the concept generation characteristics. This capability can be applied to modify any the sampling tool parameters based on the subject response. For example, the task can be terminated when the concept generation rate drops below a specified threshold.
- The system may be distributed electronically.

The tool was developed for use by novice engineering designers but is flexible enough to be used in any creative domain that seeks to expose students to issues and opportunities associated with idea generation. Upon completion of a concept generation task, the sampling tool provides the following data: design scenario attributes; concept generation frequency; cumulative distribution of concept generation; and, statistical analysis of the designer's concept generation characteristics (Figure 1). When applied to assess concept generation activities, several features may be identified (Leary and Burvill, 2005): a linear "burst phase" where concepts are generated as some constant rate; a response ceiling, which represents the maximum number of responses generated by the design team; an asymptotic exploratory phase; and, a series of concept droughts, where the design team are unable to generate any concepts for an extended period of time (Figure 1).

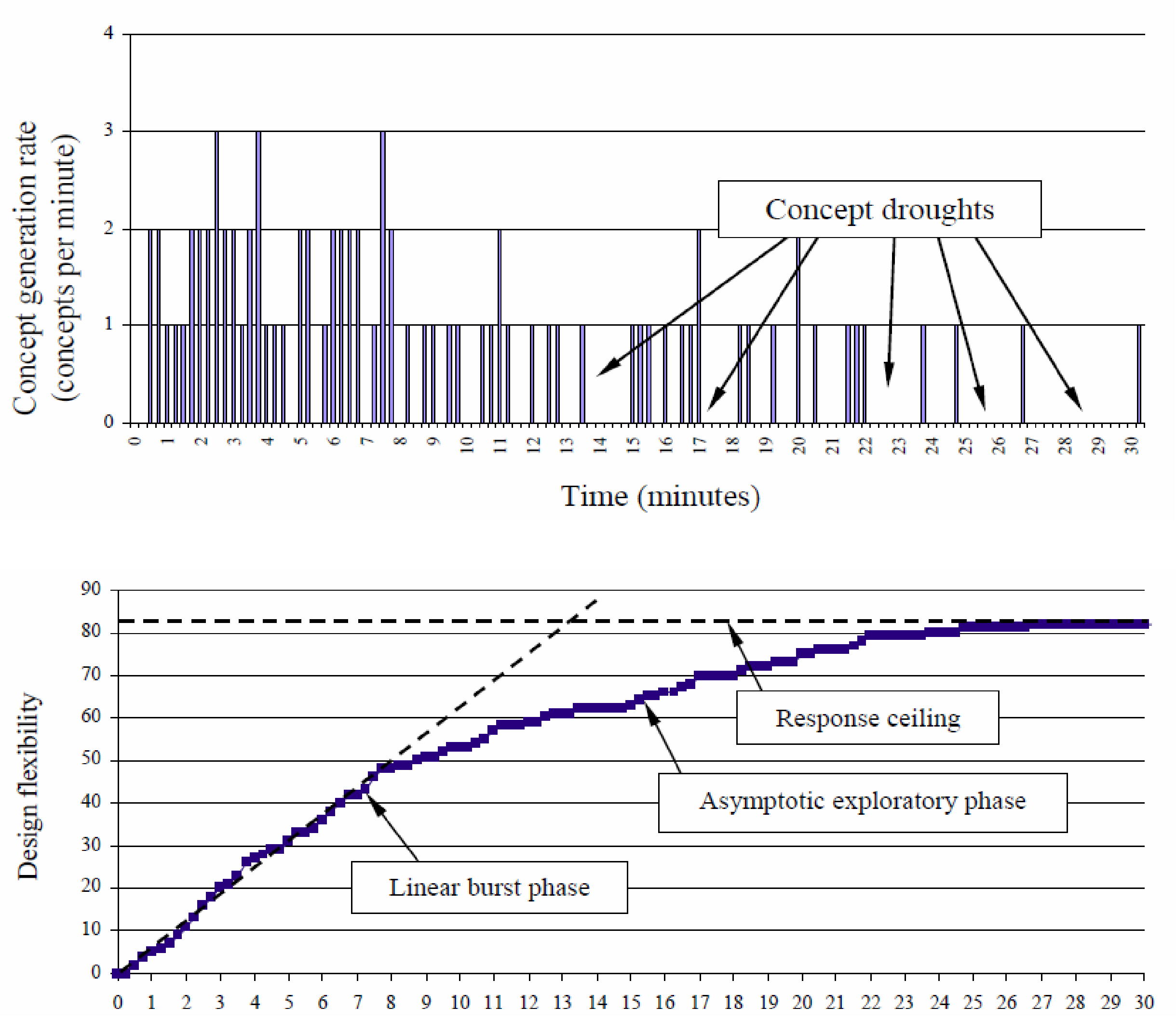


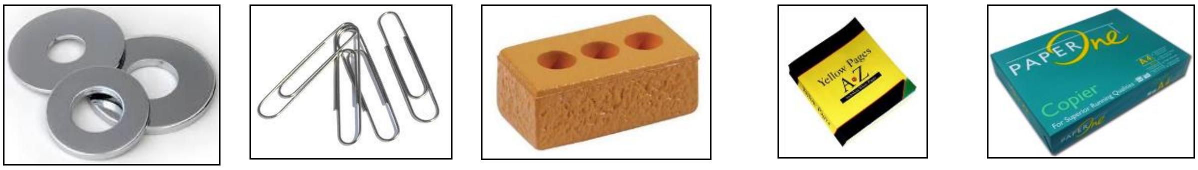
Figure 1: *Time-based summary of the response of the team (Leary and Burvill, 2005).*
Upper: Concept generation rate (concepts per minute).
Lower: Cumulative sum of concepts generated by the design team.

5 TESTING SCENARIO

Students in undergraduate Mechanical Engineering degrees at two distinct universities were selected to be involved in this program. These novice designers were involved in a senior design class, and self-selected their own group of three students to complete the concept generation task. A total of 15 design teams were involved.

As per the one-dimensional problem solving activity defined by Adams (2001), the design teams were advised that, *"The manufacturer of your product is experiencing financial difficulty. You have been hired to identify as many alternate uses of the product as possible."* Design teams were provided with unlimited access to the computer based assessment tool and were allowed to conclude the concept generation activity at their discretion.

A double blind system was applied to this study, to assess the concept generation outcomes of the novice designers both before (i.e. Scenario 1) and after (i.e. Scenario 2) introduction of the identified formal methods to enhance creativity (Section 2). One of a series of common products was provided at random to design teams (Figure 2) to ensure that concept generation outcomes are independent of the selected product. A different product was applied for each of Scenarios 1 and 2.



Washer(s) Staple(s) Brick Phone book Ream of paper

Figure 2: *Simple products provided to design teams.*

6 SUMMARY OF RESULTS

Responses from the novice designer groups was documented before and after the students were exposed to the formal methods described in Section 2 (Scenario 1 and 2, respectively). Outcomes from this study are summarised as follows (Figure 3 and Table 1):

- Qualitatively, the fluency of the concept generation outcomes appears to be superior for Scenario 2 than for Scenario 1.
- The scenario-average concept generation rate is higher for Scenario 2 (Figure 3, lower).
- The scenario-average number of concepts generated, as well as the total time before the concept generation activity was abandoned was larger in Scenario 2 than Scenario 1 (Table 1).

However, not all teams displayed an increase in concept generation outcomes after the introduction of formal methods to enhance creativity. For example, groups E, F, G, I, K and L showed a decrease in the number of concepts generated in Scenario 2.

Table 1: *Attributes of Scenario 1, Scenario 2 and percentage change for each group.*

	Scenario 1		Scenario 2		Change	
Group	No. of concepts	Total time (mins)	No. of concepts	Total time (mins)	No. of concepts	Total time
A	13	4	22	20	69%	400%
B	22	20	26	18	18%	-10%
C	25	20	48	20	92%	0%
D	17	20	66	14	288%	-30%
E	39	15	30	19	-23%	27%
F	12	18	8	10	-33%	-44%
G	53	19	32	19	-40%	0%
H	18	20	51	20	183%	0%
I	50	20	47	20	-6%	0%
J	4	5	14	18	250%	260%
K	43	19	29	3	-33%	-84%
L	16	20	12	20	-25%	0%
M	4	5	58	20	1350%	300%
N	36	20	39	20	8%	0%
O	48	20	68	20	42%	0%
					143%	55%

7 CONCLUSIONS

Students in undergraduate Mechanical Engineering degrees at two distinct universities were involved in a program seeking to enhance the capability of novice engineers to generate concepts. Of the measures presented in TTCT, only fluency and flexibility can be measured without expert assistance. Furthermore, direct measurement of both fluency and flexibility is unnecessary as both measures are highly correlated.

A self-administered, computer based tool was developed to assess the fluency of a novice engineering design groups in response to a single-dimension concept generation task. Based on the study reported in this paper, it appears that the introduction of formal methods for enhancing concept generation has an overall positive effect on the concept generation capabilities of novice designers. However, this is not definitive as enhanced concept generation outcomes was not evident in all design groups in the study.

A follow-up study is under development to further investigate the diminished performance of some teams with a view to developing a mastery learning pedagogy where gains are made by the vast majority of novice designers, with minimal additional academic teaching overhead.

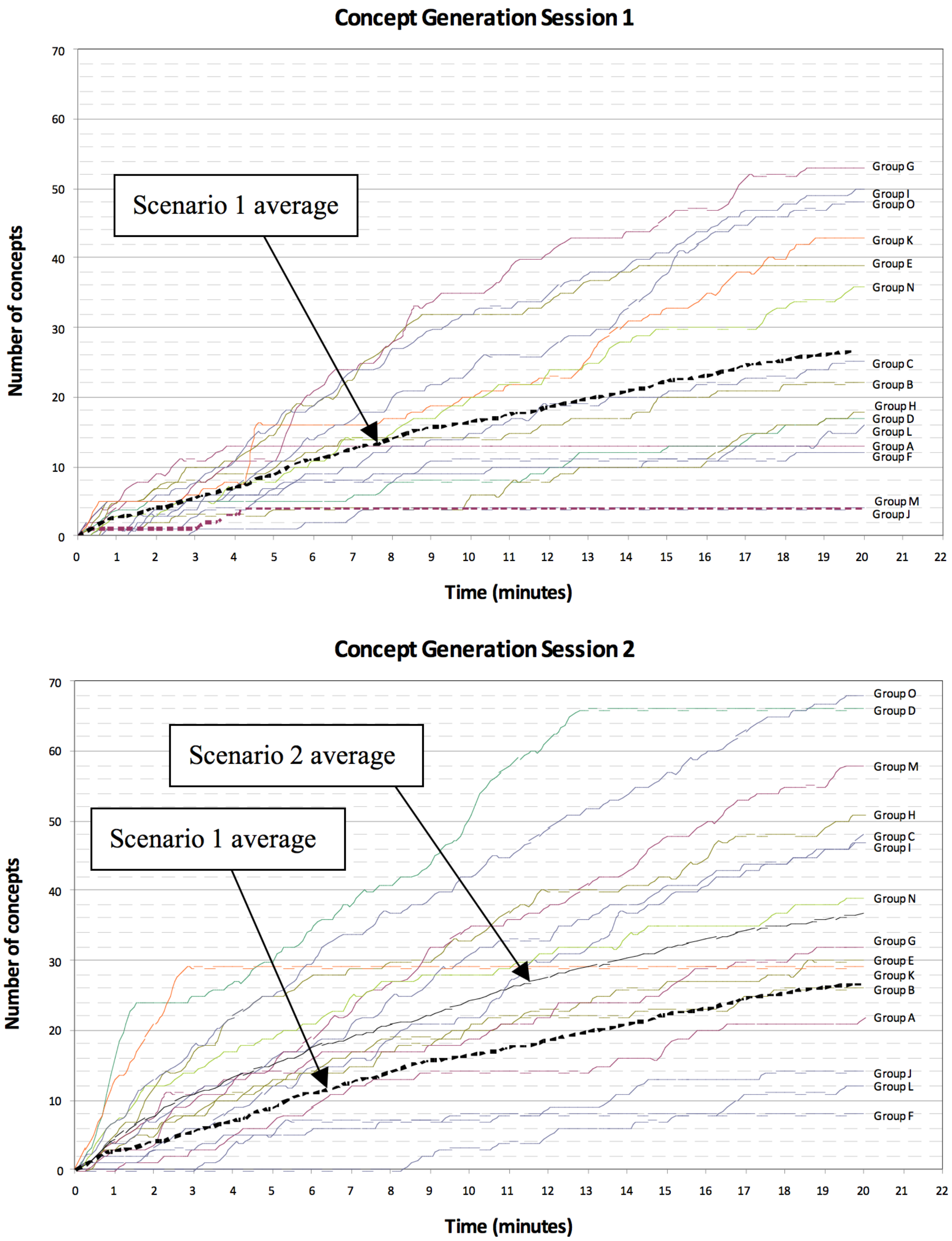


Figure 3: *Concept generation results for all Groups in Scenario 1 (upper) and Scenario 2 (lower). Scenario 1 average: dotted black line, Scenario 2 average: solid black line.*

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