Sources of creativity stimulation for designing the next generation of technical systems: correlations with R&D designers' performance

Sara Saliminamin, Niccolo Becattini, Gaetano Cascini
Politecnico di Milano, Italy

Abstract

This paper presents the outcomes of an exploratory research to clarify the performance of R&D designers when involved in design task for the ideation of the next generation of a technical system. The research aims also at clarifying if creative stimuli play a role in supporting ideation after idea generativity decreases because of natural exhaustion or the emergence of fixation. The effect of precedents (singular as patents, and structural as technology evolution trends), as well as design strategies (in the form of a design procedure for inventive problem solving) on idea generation, is compared by means of an experiment involving 24 R&D Iranian engineers. Precedents demonstrated to be more effective than design strategies in supporting productivity in idea generation, while generally they are not effective enough to support the generation of candidate ideas for the next generation of a technical system with a robust repeatability. The main recorded lacks depend on the capabilities of creative stimuli to support the generation of novel ideas, as they are generally effective in providing good results with reference to technical plausibility and relevance for a target audience. The results of the experiment are also discussed with reference to the efficiency of the design process (number of generated ideas per time unit).
The outcomes of such studies, as part of a broader research objective, serve as input to support the development of a serious game to support R&D engineers to face design tasks for the next generation of technical systems with higher motivation and engagement, providing them with an improved design experience.

Keywords: technological shifts, radical innovation, novelty, creative stimuli, design precedent, design strategies, design models

1. Introduction

Designing the Next Generation of Technical Systems (NGTS) is a very specific and crucial design task, as its output (design concepts, proposals), once engineered, can change the market interest and therefore undermine the other companies' products position in the market. The cyclonic vacuum cleaner (with less dusty air to the surrounding), as well as the automated vacuum cleaner (which detects rubbish), are examples of attempts of companies to substitute existing vacuum cleaners with the next generation of such products and become market leaders. Technological product innovations account for one fourth to one third of organizational growth (Zirger, 1990; Lee & Sukoco, 2011). Innovation helps firms to grow and compete. Radical innovation, defined as fundamental changes for new products as revolutionary technology shifts that also meets the appreciation of the market (Ettlie et al., 1984; Dewar & Dutton, 1986; Song & Thieme, 2009), provides firms with better position and performance outcomes (Germain, 1996). Despite there is no explicit mention to "design for NGTS" in design literature, the generation of ideas determining a technological shift that also have high innovation potential is a very specific design task that becomes particularly crucial in any industrial context, especially where the competition is based on the acceptance of new products by the market. A relatively wide thread of scientific literature, therefore, focused the attention on what can stimulate the generation of extremely novel ideas of high quality (e.g.: Heylingen et al, 2007; Fu et al, 2013).
In this context, R&D Engineers are expected to be the most active players in design for NGTS tasks and they should be put in the condition to fluently generate ideas that have good chances of becoming a radical innovation. Nevertheless, most of the existing literature that deals with inspiration to generate novel and

high quality ideas explored the effects of creative stimulation with experiments that just involved students (e.g. Zahner et al., 2010; Tseng et al., 2008; Doboli et Umbarkar, 2014), highlighting that tailored methods and tools for R&D engineers to face this highly creative design activity are still lacking. With a more professional-oriented perspective, one of the closest contributions available in literature deal with the application of solution-oriented technology forecasting techniques (Cascini, 2012), despite this is originally a more strategy-oriented activity. Moreover, that contribution presents methods and tools that aim at supporting professionals, but it also claims that professionals find some of the proposed approaches too complex or too rigid for application (e.g. ARIZ, as for Altshuller, 1988) and there is no new experimental evidence calling into question this statement.

In fact, academically developed methods and tools to improve design effectiveness and efficiency are just slowly penetrating industrial practice (e.g.: McMahon et al, 2016; Fiorineschi et al., 2018), because designers and R&D engineers usually find them too rigid and time-consuming for their consolidated ad-hoc, unsystematic (Cross, 2001) and opportunistic way of designing (Visser, 1990).

According to the abovementioned aspects, which limit the engagement and the proficient creative stimulation of professionals, it appears reasonable to leverage designers' creativity by exploiting different modalities of interaction with design methods and tools. The authors believe that the introduction of a ludic dimension in the design process, within this kind of open-ended task, can help R&D engineers and designers to overcome some of the barriers hindering the adoption of design methods and tools and facilitate the engagement among colleagues. Serious game, in fact, are riding high as a market trend and some items for leveraging creativity with appropriate stimuli, through game-based communication channels, are already available for purchase on e-marketplaces, e.g. https://goo.gl/n1JUZF.

This research is a first step towards the development of a serious game to support R&D engineers in designing the next generation of a technical system. Two main elements are needed to design a serious game and help gamers to develop their skills: a right balance between the active involvement of owned skills and, through learning-by-playing, the development of new ones. In details, this paper focuses on the effects that different creative stimuli have over a collaborative ideation process for the NTGS, as a refined version of them will be tuned for the game mechanics (to be completed, based on the outcomes of this research).

The paper has the following structure: first, an overview of the research methodology to frame the paper content with respect to the research activity. Then, previous findings in design, cognition and creativity literature are presented and discussed to develop both a preliminary set of tailored creative stimuli and appropriate metrics for the assessment of candidate ideas for the next generation of technical systems. Section 5 deals with the setting, the design task and other details of the experiments that involved 24 R&D Engineers, together with the rules for data acquisition, assessment and processing. The results of the experiments and a discussion of the main evidences, with reference to previous findings are, respectively, in Section 6 and 7, just before the conclusions.

2. Research questions and methodological approach

As briefly mentioned in the introduction, this paper aims at informing the early stages of the development of a serious game to support R&D engineers in conceiving the NGTS. The IDEF0 (IDEF is for Integrated DEFinition, a family of modelling techniques – http://www.idef.com) diagram in Figure 1 presents an overview of the research methodology. Within IDEF0 models, each box of the diagram represents an activity that is detailed with brief textual description (middle of the box) and labelled with a letter and a number (lower right corner, e.g. A1).

Consistently with such modelling notation, in Figure 1 every activity carried out along the research aims at transforming an input into an output. Inputs and outputs are represented as arrows that are, respectively, incoming (left side of boxes) and outgoing (right). Arrows that enter boxes from below represent the resources required to carry out that action. With reference to Figure 1, these resources can be human (e.g.

experiment manager and participants), tangible (e.g. pen and paper used for the experiment) or intangible (as the contents for creative stimulation, despite they were represented on paper).
Arrows that enter boxes from top represent the set of rules which controls the execution of the activity. In Figure 1 these rules correspond to the metrics for the assessment of candidate NGTS ideas as well as the definition of experimental groups and data acquisition protocol.
It is worth noticing that outputs of an activity can be used as inputs for next ones (e.g. the design task defined in box A1 is the input for the execution of the design session, as for box A3), but also as resources (this is the case of creative stimuli generated after the activity labelled A2) as well as controls (i.e. the rules used to run the activities, as for two of the outputs of A1, which are control for A3 and A4).

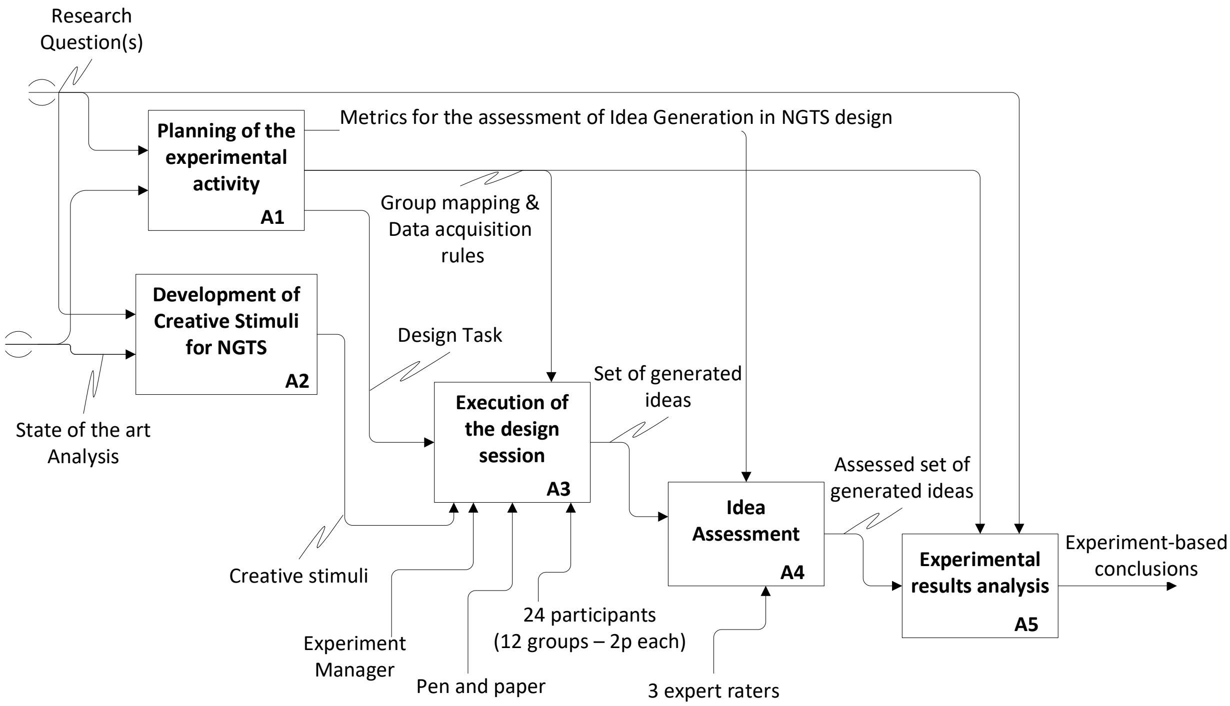


Figure 1- IDEF0 diagram of the research activity

Due to the scarcity of information concerning the outcomes of the ideation process for this specific kind of design task, this paper more specifically aims at gathering initial insights about ideation performance in such a context, with and without the support of creative stimuli. This means answering research questions as: "what is the average R&D engineers' performance to generate candidate ideas for NGTS?", "Do different stimuli produce different effects on R&D engineers' performance to generate candidate ideas for NGTS?" (these are inputs for activities A1 and A2).
Then, the authors propose an experiment to start gathering evidence about the above questions, as well as metrics to evaluate design outcomes, still with reference to the research objectives. As the literature does not directly address NGTS, relevant contributions were searched among those dealing with related concepts as characteristics of radical innovation, general criteria in assessing design and idea generation sessions (A1-Section 3 of the paper). As well, stimuli used to boost designers' creative performance in design sessions are explored as a means to improve idea generation (A2- Section 4). Those findings support the development of both the creative stimuli and the metrics for the experiment. After running the design session of the experiment according to the planning (A1 and A3 – Section 5), the ideas generated along the experiment get assessed by a panel of 3 experts that rank them according to the metrics (A4). Such results, measured by counting the number of ideas satisfying specific threshold values for the tailored metrics, allow drawing preliminary conclusions on idea generation for NGTS with and without creative stimulation (A5 – Section 6 and 7).

3. Measuring candidate ideas for the next generation of technical systems

This section discusses NGTS with reference to relevant literature on innovation, to highlight their main characteristics. Then, it proposes tailored metrics, also with reference to creativity metrics, for the assessment of radical ideas suitable for developing NGTS.

Several terms in literature can be referred to NGTS, despite this expression is never explicitly mentioned: radical innovation; radical technological change; technology paradigm shift; technology-push innovation; market-pull innovation; design-driven innovation; breakthrough innovation and radical novelty. E.g. in Cooper & Schendel (1976); Dosi (1982); Coombs et al. (1987); Anderson & Tushman (1990); Christensen & Rosenbloom (1995); Tripsas (1997); Geels (2004); Verganti (2008). The abovementioned contributions classify radical innovation with respect to different factors as the magnitude, the drivers and triggers of innovation. The magnitude of innovation implies that an NGTS shows significant changes with respect to the previously existing system, instead of minor adjustments/improvements typical of incremental innovation (Trott, 2008).

Market (Caves & Porter, 1977; Porter, 1979; Johne, 1999) and technology (Pavitt & Wald, 1971; Rosenberg, 1976; Mowery & Rosenberg, 1979; Pavitt & Soete, 1980; Soete, 1981; Dosi, 1982) are two main drivers of innovation, as scholars usually recognize and explain innovation from a technology-push or a market-pull perspective.

Interest in radical technological change originated with Schumpeter (1934). He was one of the first to claim that radical technological change is a powerful mechanism that can challenge the power of monopolists (i.e: replacing well-established solutions). Later on, the literature focused on product characteristics to explain drivers of innovation. Improvements of functionality (generally coming from technology-push innovation processes) and the customer-centred perception and interpretation of design (generally due to market-pull innovation processes) are two of them. Shifts in technological paradigms are often coupled with shifts in socio-cultural contexts (Geels, 2004), therefore it is not uncommon that a technological innovation implies the users perceive the proposed solution with a new meaning. And such a meaning typically deals with the satisfaction of users' utilitarian needs, including affective and socio-cultural ones (Verganti, 2008). Designers give meaning to products by using a specific design language through a set of signs, symbols, and icons (style is just an example of this), which deliver the message (Pucillo et al., 2016).

Table 1 summarizes the main characteristics of innovation (using a retrospective approach) with reference to the sources they come from.

Main characteristics of radical innovation as the characteristics of the next generation of technical systems	Retrieved from
Completely new or significantly different in meaning or functionality	
○ Useful	Patent Law
○ Wider expectations for same market (New requirements of same users)	Schilling (2010)
○ Same or wider expectations for a new market (Same or new requirements for new users)	Schilling (2010)
○ New meaning or new language	Pucillo et al. (2016); Verganti (2008)
○ Conquer the market dominantly	Verganti (2008)
New technology (in one of the scopes of hardware, software or orgware)	
○ Acceptable but not obvious to field experts	Patent Law
○ Acceptable level of novelty by the market	Shane (2001); Dahlin and Behrens (2005)
○ Constitutes the core of the change	Silverberg (2002)
○ New combinations of selected principles derived from natural sciences and selected material - Recombining already established elements	Fleming (2001)

o	Bringing in an established element into a new setting	Hargadon and Sutton (1997); Van de Poel (2003)
o	Resolving contradictions	Bledow et al. (2009); Altshuller (1988)
o	Less costs, harms and efforts/resources consumptions	Borgianni et al. (2012); Becattini et al. (2015)

Table 1- Features of radical innovations as extracted from the mentioned references. To be used to characterize NGTS.

The above list of features shows two main pieces of evidence. First, radical innovations can be identified with certainty only after observing a positive reception by the market. Second, novelty strongly connotes innovation. The former means that ideas and concepts are hard to classify as radically innovative because of their level of abstraction and vagueness, despite this could be beneficial for strategy plans in companies. The latter, in turn, shows that novelty belongs to several aspects. New user, new meaning, new language/interpretation, a new combination of principles and setting are descriptors of the changes the innovation brings, even if with reference to a specific context. Nevertheless, the evaluation of the design proposal for NGTS has to take into account the above characteristics, as radical innovations directly stem from radical ideas.

Different authors in design creativity literature have proposed criteria for idea evaluation, with reference to different purposes (Massetti 1996; Gero, 1996; Wierenga, & Bruggen,1998; Shah et al., 2003; Nijstad et al. 2002; Howard et al., 2006; Perttula & Sipilä, 2007; Howard et al., 2008; Linsey et al., 2010; Runco & Jaeger, 2012). Two main threads can be recognized for idea measurement: number/quantity of ideas (Nijstad et al. 2002; Shah et al., 2003; Perttula & Sipilä, 2007) and quality of ideas (Wierenga, & Bruggen,1998; Shah et al., 2003). The mixed approach of Shah et al. (2003) measures ideation effectiveness of design processes (NGTS design represents a specific one) according to four characteristics:

- quantity of ideas (number of ideas);
- variety of ideas (diversity of ideas, as a measure of the exploration of the design space);
- novelty of an idea (novelty with reference to existing technical system - ex-ante evaluation - or as the originality among the ideas - ex-post evaluation);
- quality of an idea (capability to address the objectives successfully).

With reference to quality metrics, some authors share the same vision and talk about "appropriateness", others focus on "unexpectedness" (un-obviousness) with respects to the target task (Massetti 1996; Gero, 1996; Howard et al., 2006; Howard et al., 2008; Runco & Jaeger, 2012, Becattini et. al, 2015). Linsey et al. (2010) consider quality as an index related to the technical feasibility of generated ideas.

As briefly mentioned above, the novelty of an idea can be seen from two angles. One is the technological perspective, which corresponds to the diversity from the state of the art. The other is the market-oriented one, which entails the new user's interpretation of the technical system, i.e. its meaning, which also deals with the capability of satisfying different/new needs. Within the scope of this paper, and in line with the design creativity literature, novelty is for assessing the diversity with reference to the state of the art in technology.

As existing metrics cannot capture the capability to breach new/different markets, this requires the introduction of a novel criterion. For the above considerations, the authors think that "relevance" (for a target audience) can be a good candidate to map the idea with respect to existing or potentially emerging markets.

These two criteria, however, are not sufficient to map design ideas and identify candidates for NGTS. Ideas should be also assessed in terms of their "time-to-market" and, if adopted, become innovations. To this purpose, the dimension of "quality", here meant as technical feasibility (Linsey et al. 2010), is a good candidate to grab the chances of the idea to be turned into a product ready to reach the market.

However, the intrinsic radical nature of candidates for NGTS allows for a more futuristic vision, while the current (hic et nunc) viewpoint on technical feasibility would be limiting. To this purpose, here the metrics to grab the capability to reach the market takes the name of "technical plausibility". In fact, R&D engineers (target audience of the creative stimuli) typically have the expertise to figure out reasonably feasible solutions that can sound futuristic for outsiders.

As technical experts should use the metrics to score ideas and identify a candidate for NGTS, a 4-level Likert scale differentiates scores for each criterion. Table 2 shows the 3 criteria above defined as metrics (novelty, relevance and technical plausibility) and the related scores (with their description). The metrics are also mapped to the characteristics of radical innovation already presented in Table 1.

Criteria	Score/criterion	Mentioned characteristics in literature
Novelty	1. Existing in the market/Already in use 2. Existing concept, not available on the market 3. Existing feature or trait in other fields of application, never applied to the domain of this product 4. Novel feature or trait	- Completely new or significantly different in meaning or functionality o Useful o Wider expectations for same market (New requirements of same users) o Same or wider expectations for a new market (Same or new requirements for new users) o New meaning or new language o Conquer the market dominantly - New technology (in one of the scopes of hardware, software or orgware) o Acceptable but not obvious to field experts o Acceptable level of novelty by the market o Constitutes the core of the change o New combinations of selected principles derived from natural sciences and selected material o Recombining already established elements o Bringing in an established element into a new setting o Resolving contradictions o Using slack resources o Less costs, harms and efforts
Technical plausibility	1. Against laws of physics 2. Not against laws of physics, but sounds infeasible 3. Sounds infeasible with current knowledge but presumably achievable with further research in the field 4. Sounds feasible with current knowledge	- New technology (in one of the scopes of hardware, software or orgware) o Constitutes the core of the change o New combinations of selected principles derived from natural sciences and selected material o Recombining already established elements o Bringing in an established element into a new setting o Acceptable but not obvious to field experts
Relevance	1. Neither for the current usage of the system, nor for potential interpretations for the future society 2. No benefits foreseen for the current usage of the system in the current society, but potential relevance in specific (narrow) niches of members of future society	- Useful - Wider expectations for same market (New requirements of same users) - Same or wider expectations for a new market (Same or new requirements for new users) - New meaning or new language Acceptable level of novelty by the market - Conquer the market dominantly

	3. No benefit for the current usage of the system in the current society but potential benefits (interpretation) perceived for different usage in a future society 4. Benefits also for the current society	

Table 2- Criteria and sub-criteria for assessing candidate ideas for the next generation of the technical systems (references as for Table 1).

Table 2 shows partial overlapping for the three metrics. Nevertheless, the repetition of some characteristics of radical innovation in more than one criterion is the unavoidable consequence of the nature of radical innovations, as technological leaps are usually tangled with societal changes (Geels, 2004).
Experts will use these criteria to evaluate and rank ideas according to the levels described in Table 2. Candidate ideas for NGTS should be selected among those reaching or overcoming a threshold score (more than 2) for each of the three criteria. Candidates and ideas, in general, will be then measured in quantitative terms.

4. Tailoring creative stimuli for NGTS-design and R&D engineers

The literature on design stimuli can be studied according to very different perspectives. Contributions on stimuli take into account different contents/domains (e.g. biological/technological sources of inspiration); communication channels/modalities (e.g. textual/graphical) as well as the analogical distance between the source of inspiration and the target system to be designed. As this research aims at developing creative stimuli for NGTS, literature should be explored accordingly. The analysis of the state of the art show there exist no direct references about NGTS-oriented design stimuli. Nevertheless, there exist researches focusing on the proficient generation of novel ideas, e.g. on high-level generativity (Le Masson et al, 2016). As the effects of design stimuli have been typically studied in design cognition literature, it seems reasonable to investigate potential sources of creative stimulation consistently with the two main families of methods and tools there explored. On the one hand, the search should focus on methodological approaches e.g. design strategies, procedures… On the other hand, it should focus on precedents, e.g. examples, hints… The following subsections first, briefly reviews and discuss precedents (4.1) and strategies (4.2) as generally representative of two different families of design stimuli, then it presents the rationale behind three different developed sets of creative stimuli for designing NGTS.

4.1. Design precedents

Precedents in design are defined as designer's prior knowledge and experiences. Moreover, precedents also include contents from any other source provided to designers as a means to allow them to access memory and foster thinking (Jones & Thornley, 1963; Tulving, 1991; Visser, 1995; Eckert & Stacey, 2000; Pasman, 2003; Lawson, 2004; Dix, 2004). Precedents are typically proposed as stimuli/idea triggers that leverage different modalities of communication/channels of representation (e.g. graphical, textual, mixed…). Pasman (2003), Lawson (2004), Eilouti (2009) explored prior solutions of the target technical system. Linsey et al (2010) studied the effect of a collection of examples of other technical systems, distinguishing close or far domains with reference to the target technical system. Others focused on hints for considering requirements (Downing, 2003), templates describing an entire class of solutions (Senbel et al., 2013) or hints about specific characteristics of prior solutions or other examples such as function and behaviour

(Doboli & Umbarkar, 2014). Such kind of studies usually measures the effects of stimulation directly on design proposals, e.g. the outcomes of the design session or process.
Precedents are provided into two main forms to designers during design sessions. One or an unstructured collection of prior solutions for the target technical system, as well as relevant designs and examples of other technical systems, are typically considered examples of singular precedents. On the other hand, they can come as a structured representation of previous knowledge and experiences. Heuristics, ways of designing, templates of an entire class of solutions, solution characteristics or hints are examples of structured precedents. In both these two forms, the inherent goal is the same: precedents should be capable of supporting an effective and efficient design thinking, so as to trigger a fluent idea generation processes.
Previous researches show that the effects of different precedents are mostly studied with respect to the quantity, novelty, variety of the design results; while fewer studies consider quality and utility. Table 3 summarizes the main findings of the reviewed studies.

Type of Precedent	Dimension of Creativity	Positive effect on specific dimensions of creativity	Negative effect on specific dimensions of creativity	Positive effect on creativity
Generic (not specified)	Novelty	Akin (2002); Eilouti (2009); Gonçalves et al. (2013);	Chua et al. (2008); Heylighen et al (2007)	Ishibashi & Okada (2006)
	Quantity			
	Variety			
	Quality			
Singular precedents	Novelty	Chan et all (2011); Dunbar (1997); Fu et al (2013); Linsey et al. (2010); McKoy et al (2011); Moreno et al. (2014, 2015); Tseng et al (2008); Weisberg (2009)	Jannson & Smith (1991); Smith et al. (1993)	Nijstad et al. (2002)
	Quantity	Simonton (2010); Tseng et al (2008)	Jannson & Smith (1991); Purcell & Gero (1992)	
	Variety	Benami & Jin (2002); Crilly (2015); Kershaw et al (2011); Mak & Shu (2008); Simonton (2010); Toh et al. (2013); Youmans (2011)	Helms et al. (2009)	
	Quality	Dunbar (1997); Weisberg (2009)		
Structural Precedents	Novelty	Goldschimdt (2011); Oxman (1990); Zahner et al. (2010)		Marslen-Wilson & Tyler (1980)
	Quantity	Liikkanen & Perttula (2006)		
	Variety	Lane & Jensen (1993); Luchins (1942)		
	Quality			

Table 3- Previous studies about effects of different kind of stimuli on the design proposals

Table 3 collects 34 different published studies. 6 out of 34 (20,6%) studies generally discuss the effects of precedents, while 21 (61,7%) and 7 (17,6%) focus the effects of singular and structural precedents respectively. The effects of precedents are also considered according to the main dimensions of creativity presented in section 3, as these are crucial indexes describing the idea generation effectiveness of the proposed idea triggers. The table clearly highlights that most of the evidence shows that precedents increase novelty, variety and in general creativity, though there are some studies that show contradictory results (i.e.: Chua et al. 2008; Heylinghen et al. 2007; Jansson & Smith, 1991; Purcell & Gero, 1992 and Helms et al, 2009). The table also shows that experimental outcomes are more controversial when designers deal with singular precedents and examples. Structural precedents (e.g. organized into abstract categories or paired to highlight similarities and dissimilarities), on the contrary, show a generally positive impact on the different dimensions of design creativity. A relatively recent contribution by Doboli & Umbarkar (2014), not included in table 3, considers both structural and singular precedents and for both these stimuli they noticed no specific effects on novelty (except for the stimulation with set of new requirements for which the correlation is positive) or variety (except for a slight reduction of idea diversity with generic precedents). On the contrary, the recorded a general improvement of idea quality (and utility/usefulness) due to the exposition of creative stimuli.

The above results of the investigation highlight the need for carrying out further studies on the effectiveness of precedents (stimuli/trigger) for idea generation. This becomes extremely true especially with reference to the effects they trigger on experts or professionals, as just 5 out of the above-mentioned references explore the effect of stimuli on non-student subjects.

4.2. Design strategies

Strategies in design belong to the sphere of designers' behaviour. It includes the sequences of activities (problem formulation vs idea generation) and design moves (analysis, synthesis, evaluation) carried out in the design process, as well as the time dedicated to them. Understanding the design creative process will provide information that scholars can reuse to enhance designers' creative performance as well as the quality of the solution to be designed (Howard et al., 2008).

Design cognition studies designers' thinking patterns and highlighted at least three main areas of interest: the strategy as a whole, problem formulation, solution generation (Cross, 2001). Yet, just a few of them investigated the effects of the strategies on quantity, novelty, quality or variety of design proposals. Nigel Cross' (2001) highlighted seven strategies typically used in design, as witnessed in the referenced literature contributions:

1. Considering design problems as ill-defined problems (Akin, 1978; Thomas & Carroll, 1979) that can perhaps never be converted to well-defined problems, so proceeding to find a satisfactory solution rather than an optimum (Cross, 2001);
2. Co-evolving the problem and solution until reaching a matching problem-solution pair through iterative cycles (Conradi, 1999); undertaken through exploring partial structure of design space and solution space, generating some initial ideas in the form of a design concept (Cross & Dorst, 1998), and bridging these two partial models through the articulation of the concept which enables the models to be mapped onto each other (Cross, 1997);
3. Starting design by using previous solutions as starting points to create designs with new goals, extra functions, and substructures inspired by previous designs (Pugh & Clausing, 1996; Howard et al., 2008);
4. Rapid alternation of activities, which they measured as transitions between design actions and moves (Atman et al., 1999);
5. Framing a problematic design situation by setting the boundaries, selecting particular things for attention, and imposing on the situation a coherence that guides subsequent moves (Schön, 1988). Only some constraints are given in a design problem; other constraints are introduced by the designer from

domain knowledge and/or are derived by the designer during the exploration of particular solution concepts (Ullman et al., 1990);

6. Framing five times sequentially while it is done dominantly at the beginning of the design task and reoccurs periodically throughout the task (Goel & Pirolli's, 1992); it is seldom done in one burst at the beginning of a design process (Schön, 1988);
7. Scrapping initial design ideas and starting afresh with new design concepts and a suitable amount of alternatives (Smith & Tjandra, 1998); a dominant influence is seen by initial design ideas on subsequent co-evolving problem and solution, even when severe problems are encountered and despite changes in the framing of the design situation (Rowe, 1987; Ullman et al., 1990).

The above findings have to be taken into account when developing new design stimuli as strategies or procedures. However, it is also necessary to consider that R&D engineers, as representative of design professionals, tend to use their hierarchically structured plan in a rather ad-hoc, unsystematic and opportunistic way (Visser, 1990). In fact, designers who follow a flexible-methodical procedure tend to produce good solutions. These designers work efficiently and follow a logical procedure. In comparison, designers with too-rigid adherence to a methodical procedure, or adopting very un-systematic approaches, produce mediocre or poor design solutions (Fricke, 1993; Fricke, 1996). Literature also shows that more efficient processes have positive correlations with both the quantity and quality of design outputs (Radcliffe & Lee, 1989).

In general, one of the main differences between engineering design models and creative processes in psychology stands in divergent-convergent models (Howard et al., 2008). Divergent-convergent models differ from the traditional linear style by assuming some form of integrated evaluation and selection of ideas and concepts. This is potentially a useful outlook on design from a creativity perspective, as separating the generation and evaluation periods is considered a good practice for both lateral thinking and brainstorming (Osborn, 1953).

4.3. Development of the creative stimuli

With reference to the above findings, three different set of stimuli are developed for the experiment described in this paper: two are based on design precedents (respectively singular and structural, see section 4.1) and the third one focuses on a design strategy proposed as a technological procedure for inventive design.

4.3.1. Pictorial representation of trends of evolutions of technical systems

As for Table 3, precedents generally increase quantity and novelty and diversity/variety (as they reduce fixation). Examples, especially non-textual ones, are the most common. For example, Sarkar & Chakrabarti (2008) studied the effects of different modalities of stimuli administration on design outcomes. Moreover, the positive effects of structural precedents appear to be less controversial than singular precedents.

This suggests that it can be convenient to develop one set of structured precedents to stimulate creativity as a pictorial representation of examples. This is to enable a quick and visual interaction with the example, without the need of information processing through language, which is assumed to have a stronger impact on the consumption of cognitive resources.

Templates describing an entire class of solutions are one kind of structural representation of precedents, which enable for the further composition of examples. Among them, trends of evolution of the technical system describe, each, an entire class of solutions of technical systems, generation after generation consistently with the trend recognized in technology. Trends and patterns of evolution are one of the most powerful TRIZ tools, in that they display system's evolution potentiality and speed up the generation of new solutions for technical problems (Domb, 1999; Sawaguchi, 2001; Zlotin & Zusman, 2001). The structure of such kind of stimuli is based on an evolution tree that represents the evolutionary path describing previous generations of the technical system as well as possible developments (Shpakovsky, 2006).

Technical trends of evolution, moreover, leverage knowledge that is familiar to R&D engineers, as the content of the stimuli deals with examples that are familiar to professionals with a background in science and technology.
These stimuli are proposed as five evolution trees, including one technical system each. The authors decided to develop five examples as literature does not report any evidence about the effectiveness of higher or lower number of examples to be proposed as stimuli. Appendix 1 shows the picture of the evolution tree of the five selected systems.

4.3.2. Abstract of patents related to the function of the target system

Within the stimuli considered in Table 3 for singular precedents, there are previous solutions and novel artworks typically presented as examples. This form of precedents is effective in increasing novelty and diversity if they are presented with more diversity and ambiguity (despite the mentioned controversial results).
Patents are a type of representation of novel artworks and at the same time are part of the state of the art, as they deal with existing inventions. A patent is a set of exclusive rights granted by a sovereign state to an inventor or assignee for a limited period of time, in exchange for detailed public disclosure of an invention. An invention is a solution to a specific technical problem. A patent may include many claims that define specific property rights. These claims must meet relevant patentability requirements, such as novelty, usefulness, and non-obviousness (WIPO, 2008).
Both patents about previous solutions of the target system and examples of different technical systems can be considered as possible options for creative stimulations, where the former represent near-field analogies and the latter more distant ones.
Patents, in principle, have also the advantage to be written and compiled with technical and formal language that should be understandable by readers “skilled in the art” as R&D engineers are supposed to be.
To prepare these stimuli, the summary of 5 patents related to the behaviour of target system was selected, since literature refers that this kind of precedents is also effective in increasing novelty (see Table 3, e.g. Oxman, 1990; Goldschmidt, 2011). As for the previous set of stimuli, 5 patents have been chosen for consistency. The characteristics of the selected patents are described in Appendix 2.

4.3.3. An engineering procedure for designing the next generation of technical systems

Section 4.2 presented seven strategies that designers appeared to follow with higher chances of success in design and their various nature is consistent with the ad-hoc and opportunistic behaviour of designers mentioned in the above-referenced studies. Nevertheless, it is almost impossible to stimulate designers with an ad-hoc strategy that is tailored to the specific design task. This would make it not representative of a general design situation. To overcome this limitation, the structured strategy should leverage common phases in design processes of idea emergence and problem framing. For instance, the redefinition of the new task goals and constraints, the identification of requirements and system boundaries. All these design activities to be carried out in cycles of analysis-synthesis-evaluation (Akin, 1978; Mc Neill et al., 1998; Gero & Kannengiesser, 2004). From this perspective, TRIZ-based anticipatory design approaches (Kucharavy & De Guio, 2008; Cascini et al., 2009; Cascini et al., 2011) leverage specific design models, organized as structured sequences of steps to support the above-mentioned design activities with a future-oriented goal, as it should be for NGTS. The procedure developed to stimulate R&D designers’ strategy elaborate on these approaches by integrating models in a step-based procedure. It proceeds by searching current problems and solved problems to propose the NGTS, according to the assumption that behind a problem there is a technical issue or a user’s need that sooner or later needs to be solved or made irrelevant (Kucharavy & De Guio, 2005).
Problems, as well as non-fully satisfactory situations, should be extremely familiar to R&D engineers, as they work daily to fix them and improve existing solutions.
Within the scope of the development of this stimulus, consistency with precedents can’t be kept because of the different nature of the stimulus. This said, the proposed procedure is composed of 5 steps that, on

purpose, should require an expert in the field to work for 30 minutes to complete it. Appendix 3 details the steps of the developed procedure.

The above set of stimuli were selected to inspire different groups of designers. This allows comparing the ideas they generated during the experiment using different stimuli, as described in the next section.

5. Description of the experiment and rules for data analysis

This exploratory study observes R&D engineers' performance with and without the use of creative stimuli in designing NGTS.
For what concerns the experiment dynamics, it consisted of two main design sessions: the first session carried out without any creative stimulation and the second one with the 3 sets of stimuli, as presented in Section 4.3. Each session lasted 45 minutes with a break of 10 minutes in between. This duration of the design session is consistent with the evidence that brainstorming-based design session's productivity decreases after half an hour, while the best ideas are generated during first 15 minutes (Howard et al., 2010). The design task was briefly presented to R&D engineers during the few minutes that precede the first session and did not change between the sessions. To avoid cross-effect of different stimuli on the teams, teams were randomly divided into four groups and received one different set of stimuli each for the second round. One of the groups received no stimuli in the second round and played the role of the control group. Figure 2 shows the setting of the experiment.

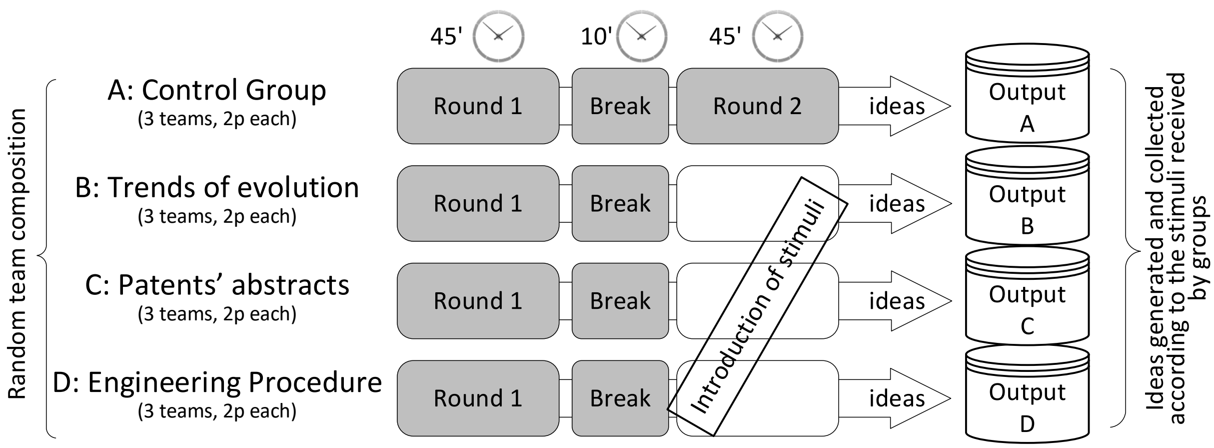


Figure 2- Experiment setting

During the first round, the participants were free to design, according to their normal behaviour and it is expected that most teams proceeded through brainstorming. Evidence from literature witnesses that traditional brainstorming is still the preferred technique in industry for producing innovation in teams (Howard et al., 2010), despite the growing body of research identifying its limitations (Isaksen & Gaulin, 2005). Since the beginning of round 2, the creative stimuli of Section 4.3 were provided to teams for each of the three groups receiving the treatment (the group receiving the procedure had limited freedom due to the sequence of steps of the stimulus). Except for the treatment, the same rules as round 1 apply. This kind of setting (1st round: no treatment; 2nd round: treatment + control group) allows checking the effectiveness of stimuli in a more demanding condition. The first round is meant to exhaust designers' generativity, making harder to find new concepts during the second round of design. This also allows for paired comparisons before and after the treatment with the same group.
24 Iranian R&D engineers participated in the experiment as members of 12 teams (2 people each). They were enrolled as subjects for the experiment after a call for volunteering engineers. The call requested for subjects having at least 3 years of experience in R&D departments of industrial companies working on new product development processes. The subjects were selected independently from the market domain of the

company they work for. Volunteers from different companies were organized in teams of two-engineers. The criterion to build up teams focused on randomization and optimization of time and human resources for the experiment execution. The profile of volunteering subjects can be summarized as follows:

- Gender: 75% male and 25% female (18 Men and 6 women);
- Ages: ranged from 28 to 40 years;
- Level of education: 12% PhD, 71% master and 17% bachelor;
- Engineering field: 37% industrial engineering, 21% mechanical engineering, 13% computer engineering, 13% electrical engineering, 8% design, 4% polymeric material engineering and 4% textile engineering;
- Experience in R&D units of Iranian companies: 67% (between 7-9 years), 16% (between 5-6 years) and 17% (between 3-4 years);

The whole experiment for 12 teams was scheduled and performed in series during one week in the summer of 2014. Each day, 2 teams worked separately, one in a morning design session and the second in the afternoon design session. This prevented members of different teams to share ideas with teams or simply individuals participating in the experiment. Participants coming from the same company and involved in different design sessions were told to discuss the design task just with colleagues that have already participated in.

Each of the 12 teams had at least one R&D engineer from the Industrial or Mechanical domain.

For what concerns the design task, the design teams were asked to generate ideas for the next generation of a domestic refrigerator. This product is a technical system everyone uses in everyday life and it holds several devices that span the most various fields of technology, so that all the participants can provide ideas from different angles. This is also done to ease leveraging prior knowledge and experience to generate and develop design ideas. All the participants were also familiar with the mechanism of cooling in a fridge, as it is part of the high school syllabus for the Iranian education system. The task was also open-ended as specific requirements were not provided. Such freedom was given in order to observe the natural behaviour of participants while they generated ideas and elaborate on them.

The participants were asked to verbally interact to make it possible to record the speech and analyse the talk-aloud protocol to identify generated ideas for further assessment. The experiment was conducted in teams of two R&D engineers in a closed room, equipped with a video recording device to record the participants' voices. They were also equipped with markers, pen and A3 paper to draw and make annotations. Figure 3 shows the setting of the experimental room.

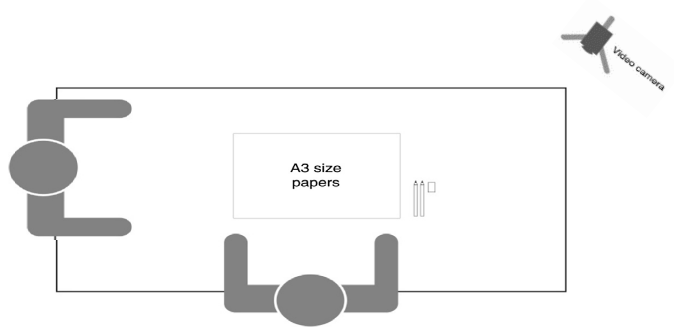


Figure 3- Experimental setting

The participants were free to use the paper as a supportive tool, but they were also asked to explain their writings and drawings, as the analysis would be limited to the verbal interactions. Teams used pen and paper in various ways. Figure 4 shows two examples: one which is rich in text and poor of drawing and vice versa.

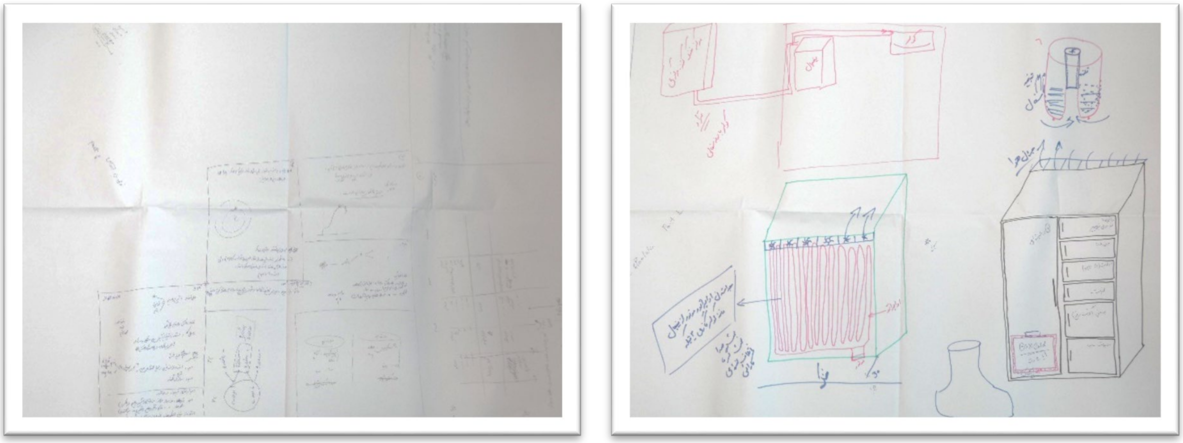


Figure 4- Two examples of notes and drawings gathered after the experiment

Three experts received the list with the whole set of generated ideas as emerged from the transcripts. They ranked each idea according to the metrics presented in Section 3. Candidate ideas for the NGTS required scores 3 or 4 by all three experts, for each of the three criteria. Ideas taking scores 3 or 4 for just one or two out the 3 metrics are considered for the evaluation of the effect of stimuli over the different categories separately. Ideas got counted once per group even if they are repeated (just first occurrences counted). Ideas are to be compared quantitatively so that it allows for comparisons between different treatments.

The general characteristics of the experts involved in the evaluation can be summarized as below:

- Gender: male;
- Ages: ranged from 30 to 50 years;
- Level of education: PhD;
- Engineering field: mechanical engineering;
- Experiences: More than 10 years experience in problems solving and technology forecasting. Solid and updated knowledge on technologies for domestic appliances.

6. Correlations between R&D engineers' performance and creative stimuli for NGTS

This section presents the results obtained during the experiment with reference to the research questions proposed in Section 2. The following subsections discuss the outcomes of ideation with and without the influence of creative stimuli.

6.1. Duration of design sessions and effects of creative stimuli

Despite the duration of 45-minutes proposed to the participants, each team dedicated a different amount of time to complete the task. (1st session: 32'-50'; 2nd: 25'-55'). Figure 5 shows that just 2 teams (16.8%) asked for more time, suggesting that the duration of the session, with or without stimuli, is correctly limited.

In addition, round 2 shows decreased durations (avg -14,5%) except for the teams treated with the engineering procedure (+13,09%). Considering the tendency of teams in the group with no treatment to spend less time in the second session, it can be supposed that the teams with the engineering procedure needed more time than what requested for applying the other precedent-based stimuli (patent, trends).

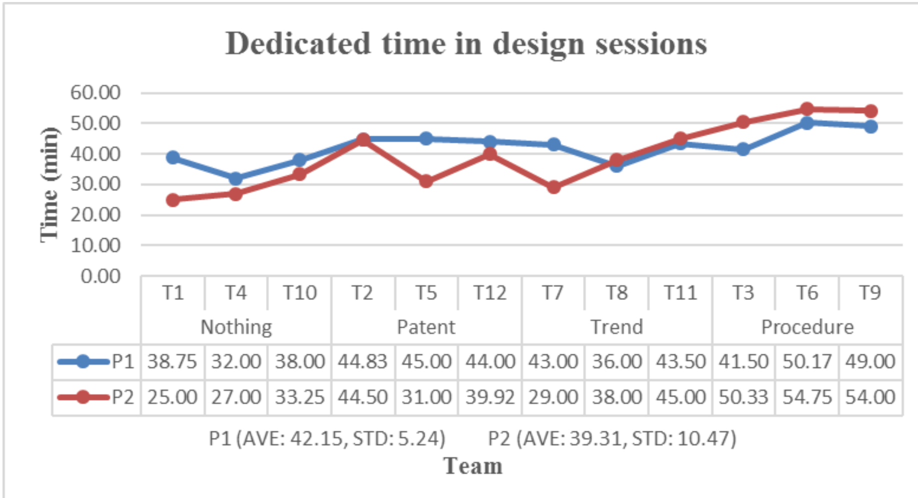


Figure 5- Comparison of dedicated time for performing the task in the first and second design sessions in respect to the kind of stimuli

6.2. Number of generated ideas (productivity) and effect of creative stimuli

The number of generated ideas is used to study productivity for uniform durations of design sessions. On the contrary, the rate of idea generation with respects to the actual duration of design sessions allows for more consistent comparisons in case of sessions that concluded after a variable amount of time. Figure 6 shows the number of ideas (left) and the rate (right) of idea generation per team.
During the two design sessions, the teams generated 462 ideas (1^{st}: 307, 2^{nd}: 155), showing that round 2 was half productive. The average number of generated ideas for each team is 26 (SE=7) for the first and 13 (SE=9) ideas for the second session. The rate of idea generation decreases for almost all teams in the second session (avg: 0,31, SE=0.26) compared to the first session (avg: 0,62, SE=0.20), witnessing the partial exhaustion after the first round.
With reference to stimuli, the number of generated ideas decreases for all teams in all groups. The same is for the rate of idea generation. As they show the lower reduction, the groups that received trends and patents generally obtained better results.

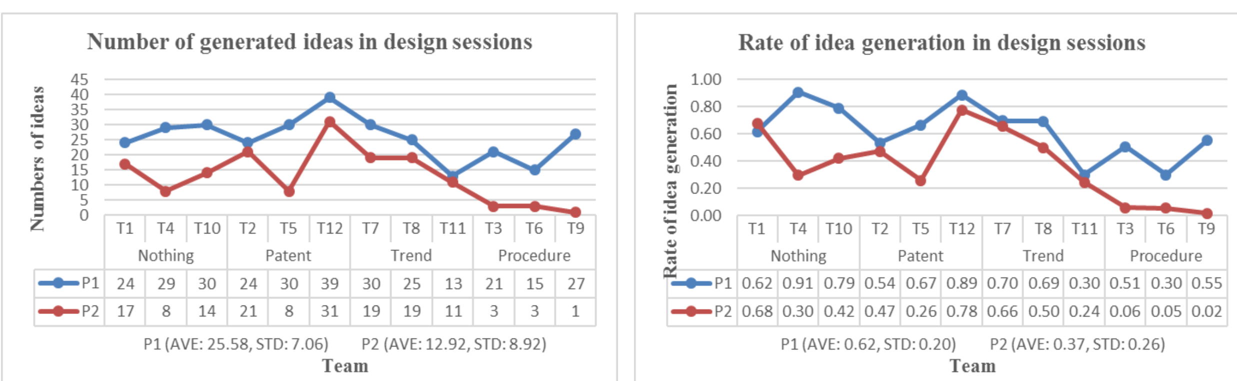


Figure 6- Comparison of team productivity in the first and second design sessions with respects to the kind of stimuli

6.3. Candidate ideas for NGTS

Candidate ideas have scores 3 or 4 on all three criteria of novelty, technical plausibility, and relevance by all 3 experts and just 16 (3.46%) out of 462 satisfy such condition. Considering the unique ideas without counting repetitions across teams (overall they are 123), just 6 of them are unique (approx. 5%). Table 4 collects candidate ideas for NGTS.

No.	Idea	Team	Time (min)
1	changing the mechanism of cooling by finding an organic element that absorbs heat for its metabolism	4	4.25
2	the size of fridge changes according to new place when we move our house	6	7.67
		5	15.17
		12	20.75
		12	21.17
		5	32.75
		9	45.25
		10	79.5
		10	81.17
3	the fridge shows the characteristics of food such as ingredients, calories, its healthiness …	8	15.25
		10	26.25
		12	60.17
4	fridge that listens to users' talks and act as a friend	2	17.83
		7	77.17
5	fridge that accepts orders and gives users the fruit or vegetables in the right time according to the ripeness	2	21.83
6	using the heat of condenser to melt ice to have purified and drinking water instead of using filters	5	44.5

Table 4- Appearance of candidate ideas in design sessions

Only 4 ideas (25%) emerged in the second session and different teams already generated them during the first session (candidate ideas for NGTS emerged at least once without any treatment). Figure 7 shows candidate ideas for NGTS by the teams and by round of emergence.

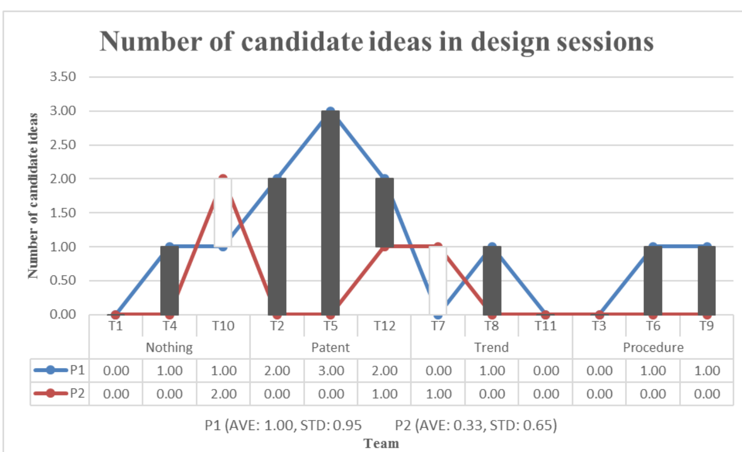


Figure 7- 1st vs 2nd round comparison of team productivity

Three teams generated 3 candidates and three generated none. Light and dark bars respectively highlight raises and drops of productivity for candidate ideas for NGTS as differences. Two light bars out of 12 (approx. 16,6%, 1 of these two occurrences is in the control group) show that none of the treatments is effective in this context.

To confirm the consistency of experts' opinions and the reliability of the criteria for assessment, the authors decided to double check the goodness of the evaluation with a second round of idea assessment. As three new equivalent experts (for expertise) were not available, the new panel consists of 9 experts. They were asked to evaluate a subset of 12 ideas, including the 6 candidate ideas as they emerged from the results of the first round of evaluation.

The general characteristics of the 9 experts involved in the second round of idea evaluation can be summarized as below:

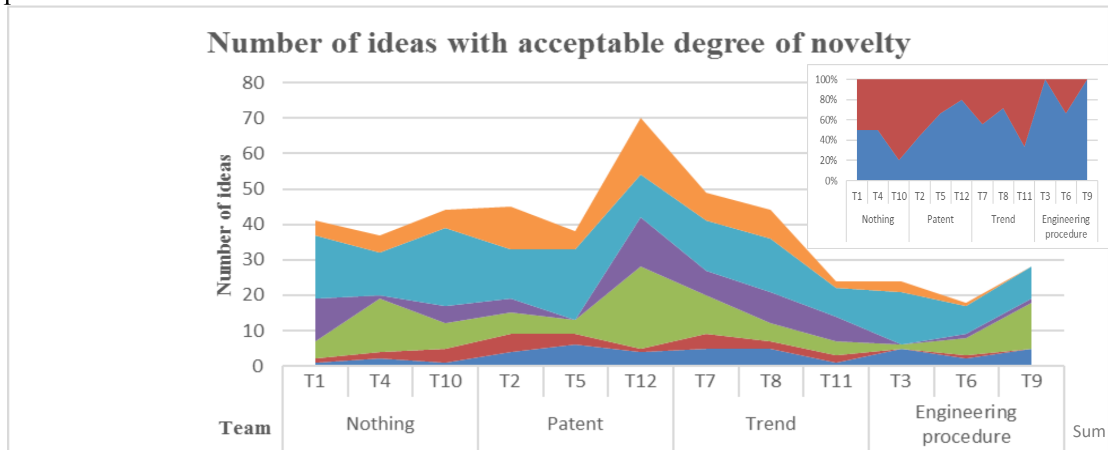
- Gender: 90% M – 10% F;
- Ages: ranged from 30 to 49 years;
- Level of education: 34% PhD and 66% Master;
- Engineering field: 68% mechanical engineering and 32% Other fields;
- Experiences: More than 10 years experience in problems solving and technology forecasting.
- Culture: 50% European and 50% Iranian;

The Interclass Correlation Coefficients (ICC) were studied for the results of the 9 experts' assessment on each of the 3 desired criteria separately. The results show 0.722 consistency (good) for Novelty, 0.905 consistency (excellent) for technical plausibility, and 0.594 consistency (fair) for relevance. The largest discrepancies for relevance might also depend on the 2 different cultures of the involved subjects. The results of this new round of evaluation confirm that the 6 accepted ideas are to be considered as candidate ideas for NGTS.

As the metrics have three criteria, the following subsections explore idea generation with and without the support of stimuli considering one criterion at a time.

6.4. Candidate ideas (NGTS) for what concerns novelty

Figure 8 shows the number of ideas with an acceptable level of novelty by all (3) or majority (2 out of 3) of experts.



Team	T1	T4	T10	T2	T5	T12	T7	T8	T11	T3	T6	T9	Sum
	Nothing			Patent			Trend			Engineering procedure			
Others .P2	4	5	5	12	5	16	8	8	2	3	1	0	69
Others .P1	18	12	22	14	20	12	14	15	8	15	8	9	167
Accepted by majority .P2	12	1	5	4	0	14	7	9	7	0	1	1	61
Accepted by majority .P1	5	15	7	6	4	23	11	5	4	1	5	13	99
Accepted by all .P2	1	2	4	5	3	1	4	2	2	0	1	0	25
Accepted by all .P1	1	2	1	4	6	4	5	5	1	5	2	5	41
Sum	41	37	44	45	38	70	49	44	24	24	18	28	462

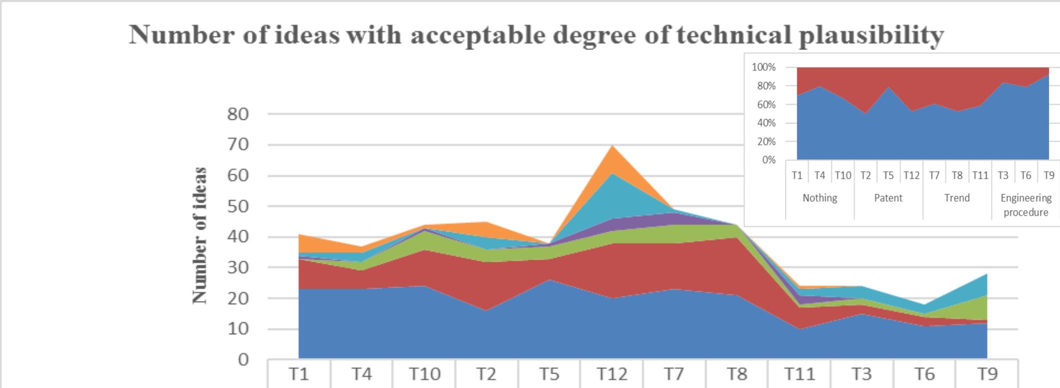
Figure 8- Level of novelty of generated ideas in first and second design sessions

66 ideas (14.29%) got scored 3 and 4 by all the experts and 160 ideas (34.63%) by the majority of them (at least 2 experts); 236 ideas (51.08%) received lower scores. Whatever the stimulus and independently from its adoption, the majority of ideas got insufficient scores to be considered candidates.

The red colour surface shows that the most effective stimuli for generating novel ideas are patents and trends. With reference to both the red and the purple surface, this behaviour is more marked, especially with reference to trends.

6.5. Candidate ideas (NGTS) for what concerns technical plausibility

Figure 9 shows the number of ideas with an acceptable level of technical plausibility by all (3) or majority (2 out of 3) of experts.



Team	T1	T4	T10	T2	T5	T12	T7	T8	T11	T3	T6	T9	Sum
	Nothing			Patent			Trend			Engineering procedure			
Others .P2	6	2	1	5	0	9	0	0	1	0	0	0	24
Others .P1	1	3	0	4	0	15	1	0	2	4	3	7	40
Accepted by majority .P2	1	0	1	0	1	4	4	0	3	0	0	0	14
Accepted by majority .P1	0	3	6	4	4	4	6	4	1	2	1	8	43
Accepted by all .P2	10	6	12	16	7	18	15	19	7	3	3	1	117
Accepted by all .P1	23	23	24	16	26	20	23	21	10	15	11	12	224
Sum	41	37	44	45	38	70	49	44	24	24	18	28	462

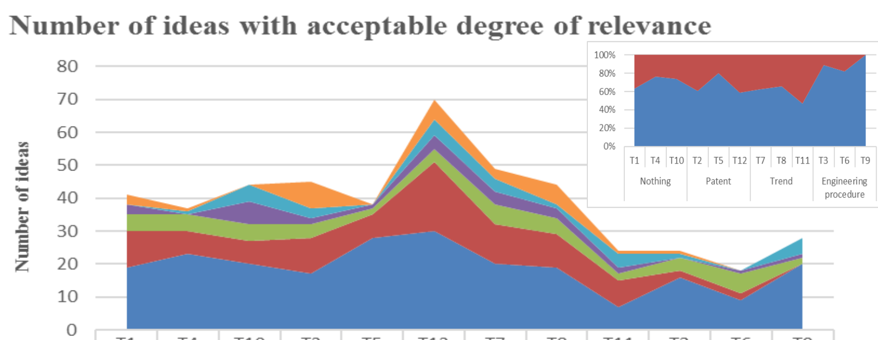
Figure 9- Level of technical plausibility of generated ideas in first and second design sessions

For what concerns technical plausibility, the whole panel agreed that 341 ideas (73.81%) are technically plausible with score of 3 or 4. Figure 9 shows that, independently from stimuli, the largest majority of ideas got scored as technically plausible.

Teams receiving trends and patents show better results, suggesting that precedents are more effective than design strategies.

6.7. Candidate ideas (NGTS) for what concerns relevance

Figure 10 shows the number of ideas with an acceptable level of relevance by all (3) or majority (2 out of 3) of experts.



Team	T1	T4	T10	T2	T5	T12	T7	T8	T11	T3	T6	T9	Sum
	Nothing			Patent			Trend			Engineering procedure			
Others .P2	3	1	0	8	0	6	3	6	1	1	0	0	228
Others .P1	0	1	5	3	0	5	4	1	4	1	0	5	98
Accepted by majority .P2	3	0	7	2	1	4	4	3	2	0	1	1	50
Accepted by majority .P1	5	5	5	4	2	4	6	5	2	4	6	2	28
Accepted by all .P2	11	7	7	11	7	21	12	10	8	2	2	0	29
Accepted by all .P1	19	23	20	17	28	30	20	19	7	16	9	20	29
Sum	41	37	44	45	38	70	49	44	24	24	18	28	462

Figure 10- Level of relevance of generated ideas in first and second design sessions

Relevant ideas scoring 3 or 4 (for a target audience) achieve the agreement of all the expert 326 times (70.56%). Also in this case, independently from the adoption of creative stimuli, the large majority of ideas have been rated as relevant and thus potentially addressing a market.

Both red and purple areas show that patents and trends (precedents) are more effective than design strategies to improve idea generation in this context.

7. Discussion

As there are no previous studies about the performance of R&D engineers dealing with an NGTS-design task, the results shown in Section 6 will be discussed just with reference to previous studies about the effect of stimuli during idea generation.

Pictorial representation of trends of evolution of technical systems (i), abstract of patents related to the function of the target system (ii) and an engineering procedure (iii) for designing the NGTS are the three types of stimuli developed and studied in the scope of this research.

In this research, the effectiveness of the proposed stimuli is studied in 12 design sessions, each of them organised into two rounds (just round 2 is with creative stimuli) for proposing the next generation of refrigerator, selected as the target technical system for the design task.

Consistently with the experiment dynamics, the first part of the experiment effectively exhausted the teams' generativity, as none of the teams generated a higher number of ideas in round 2.

To gather evidence about the effectiveness of stimuli, the changes in teams' performance for each group during the second session are considered and compared to the outcomes of the first round of the experiment. Table 5 ranks the effectiveness of stimuli with reference to the metrics adopted for this study.

No.	Performance characteristics	Ranking of stimuli with respect to their effectiveness			
		First	Second	Third	Fourth
1	Quantity of ideas	Trend	Patent	Control group	Procedure
2	Quantity of candidate ideas	Trend/ Control group		Patent	Procedure
3	Quantity of ideas with acceptable level of novelty	Control group	Trend	Patent	Procedure
4	Quantity of ideas with acceptable level of technical plausibility	Trend	Patent	Control group	Procedure
5	Quantity of ideas with acceptable level of relevance	Trend	Patent	Control group	Procedure

Table 5- The influence of different stimuli in order in the second session

The results of the experiment show that, independently from the stimulus, precedents (singular, as a patent, or structural, as evolutionary trends) are effective in triggering ideas that are relevant and technologically plausible. The results also show that trends and patents produce a positive effect in increasing the number of ideas with respect to the control group in the second session. This observation confirms the findings in Tseng et al. (2008), Nijstad (2002) and Likkanen and Pertula (2006). The effect of trends and patents on the novelty of design proposals is not positive compared to control group, while the majority of previous researches show that examples and previous solutions increase novelty; e.g. Gonçalves et al (2013), Goldschmidt (2011). Trends and patents are not effective in increasing novelty in the scope of this research, but this can also depend on the higher acceptable degree of novelty this research aims at capturing, with reference to NGTS. A biased judgement among experts can also have affected this result, as novelty assessment is strongly influenced by the previous specific knowledge they have on subassemblies of the target system in an a-priori evaluation. However, trends generally trigger a more positive impact than other stimuli as this better mitigates the drop of generativity.

A more comprehensive analysis of the results, which also considers ideas that were accepted by the majority of evaluators according to the three criteria with scores 3 and 4, show that trends (which are a specific kind of structured precedent), reduce the drop of generativity with better results than all the alternative treatments of the experiment.

Despite the above results appear to be confirming the studies of Heylingen et al (2007) and Chua and Iyengar (2008), the overall positive effect that precedents have on novelty is also measured within this experiment. Considering that the second round is less productive by design, the ratio of accepted ideas (score 3 or 4 by 3 experts) over the rejected ideas (score 1 or 2) allows checking their effectiveness after exhaustion. From this perspective, patents and trends slightly improve the results comparing the same team's performance of first and second round of a percentage around 5%.

Creative stimulation by means of a structured design strategy (the engineering procedure summarized in Appendix 3) demonstrated to be dramatically decreasing the fluency of idea generation in this kind of activities. On the contrary, it demonstrated a perfect efficiency in producing technically plausible ideas, as it is expected from a structured procedure.

The composition of design teams, as mentioned in Section 5, followed a randomization process, so that teams could be composed heterogeneously. This makes hard or just speculative any even preliminary conclusion on the effects of stimuli on R&D engineers having different expertise and background. To this regard, the experimental setting described above allows for the replication of the experiment with different controlled conditions (e.g.: homogenous expertise vs. different stimuli).

8. Conclusion

This paper aims at clarifying the performance of R&D designers involved in the ideation of the next generation of technical systems (NGTS), as literature shows several pieces of evidence of methods and tools that more or less explicitly deal with design for radical innovation, high novelty, etc. The paper clarifies what should be meant as candidate ideas for NGTS and provides metrics to assess them, as literature generically refers to novelty, while radical ideas with innovation potential should be considered from different angles. From a broader perspective, it aims at studying the effects of some alternatives among the most effective categories of creative stimuli on their performance. This is to refine creative stimuli before they will be embedded into a serious game that should facilitate R&D engineers to face design tasks for NGTS with higher engagement and motivation. An experiment involving 24 Iranian engineers working on a design task (design the next generation of domestic refrigerators) allowed for testing their performance in terms of idea generation. The quantity of ideas, with reference to novelty, relevance for a target audience and technical plausibility are considered here as the main dimensions to identify a candidate for the next generation of technical systems (the above-mentioned metrics). Three experts rated ideas and a panel of nine confirmed their initial selection of candidate ideas for the next generation of the technical system, so that the results provide new evidence with a twofold objective. On the one hand, this evaluation help shedding a light on the ideation performances with and without creative stimuli. On the other hand, it confirms the applicability of the metrics to evaluate ideas for NGTS.

The results show that free ideation (brainstorming-like) allows for a good rate of productivity, as more than 1 idea emerge every 2 minutes (0.62 ideas/minutes, 0,2 SE) among teams. Moreover, on average, the teams generated 1 candidate idea each (SE 0.95). The 12 candidate ideas for NGTS are just 6 unique ideas (some of them are repeated) and they are just 3.9% of the total ideas generated in the first session. It is important to notice that a candidate idea for the next generation of technical systems should satisfy the three criteria of novelty, technical plausibility and relevance by the whole panel of evaluators with high scores, which significantly reduced their overall amount. However, this is consistent with the nature of candidate ideas, as just a few concepts survived the whole development process and just a few of the solutions entering the market becomes actual innovations.

Nine out of the 12 selected ideas are generated in the first 30 minutes and 8 of them (89%) are generated before 22.5 minutes, which is approximately half of a design round. Next researches should consider this time frame as a reference for the duration of design sessions in similar experimental activities.

Independently from creative stimulation, approximately 75% and 70% of generated ideas have been scored, respectively, plausible and relevant for a target audience by all 3 experts involved in the assessment. From the perspective of the development of a serious game, which is the future evolution of this study, these results suggest that higher efforts should be invested in the improvement of R&D engineers' performance about novelty.

Comparing the effects of stimuli on R&D designers' performance against each other, trend and patent showed a more positive effect in increasing almost all design proposal characteristics (novelty, relevance and technical plausibility) with respect to the engineering procedure. Therefore, creative stimuli in the form of precedents appear to be better candidates for the implementation in the mechanics of a serious game to support R&D engineers to ideate candidates for the next generation of technical systems. In addition, the results showed that structured precedents as trends appeared to be more effective, compared to singular precedents (patents) for idea generation. This is confirmed considering both the overall quantity of generated ideas and the subset of candidate ones. Moreover, this kind of structural precedents provided evidence to be the most effective in reducing the drop of generativity with reference to novelty, technical plausibility and relevance. This, in turn, has a twofold consequence. For what concerns the research in design creativity, this triggers the need to carry out further studies (with new and fresh large dataset) to compare the effects of structured and singular precedents, as the results of this study substantially show an opposite behaviour compared to what recorded by Doboli and Umbarkar (2014). On the other hand, differently from the engineering procedure, which has just a structured textual set of instructions to follow, both trends and patents were both in textual and pictorial form. This shows a substantially increased effectiveness of the latter (regardless of their nature: structural or singular) against stimuli exclusively provided in a written form. However, an engineering procedure, by its own nature, is intrinsically triggering convergent thinking, so that a lower number of generated ideas is expected through its use. On the contrary, it is expected to be highly efficient in generating ideas of high quality (regardless of the metrics adopted). It is also worth recalling that the experimental dataset is based on the performance of professionals, which

constitute a significant difference with reference to most of the considered literature contributions, as experiments were typically carried out with students. Given the higher productivity of the free ideation, compared to the lower performance of R&D engineers invited to follow an idea generation procedure, the game dynamics should be capable of leveraging the already owned skills, rather than constraining the train of thoughts according to strict rules, which appear inhibiting an effective stimulation of creativity.
Besides, all the subjects participating in the experiments were from Iran. This potentially introduces a bias for the evaluation of idea generation performance, as the outcomes reflect a mindset that is potentially influenced by subjects' culture. However, the repeatability of the proposed approach enables the authors and other scholars to repeat similar studies using the same experimental setting and metrics. The results of additional experiments can be therefore used to confirm the conclusions of the present study or to highlight potential cultural differences that can be leveraged to fine-tune methods and tools on specific target beneficiaries. Further studies should be also focusing on the nature of pictorial and textual communication of stimuli of different nature, thus including those sources of stimulation that are not based on precedents.

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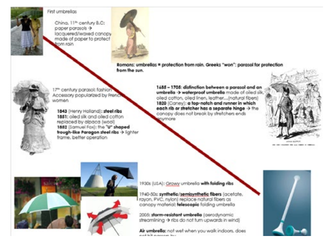
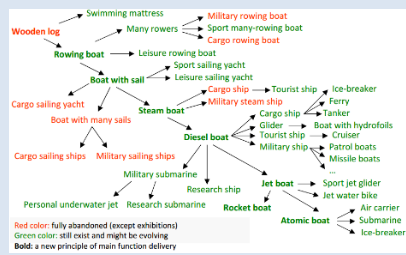
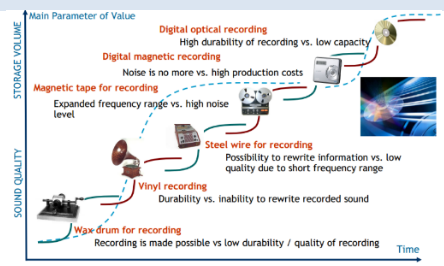
Appendix

1. Simple evolution path of five technical systems as the first form of stimulus for improving R&D engineer performances and skills in designing the next generation of technical systems

<table>
<tr><th>No.</th><th>Examples</th><th>Explanation</th><th>Picture</th></tr>
<tr><td>1</td><td>Eye glasses</td><td>To realize convenience and smartness through the following stages:
1. Two joint lenses
2. Two lenses with a handle
3. Normal glasses
4. Glasses front open
5. Google eye glasses
* bring available technology into the field</td><td></td></tr>
<tr><td>2</td><td>Umbrella</td><td>To realize better adaption to real conditions by solving the problems through new materials, fields and structures through the following stages:
1. Paper parasols
2. Ordinary umbrella
3. Non-symmetric umbrella
4. Big umbrella improved for wind
5. Air umbrella
* bring available technology into the field</td><td></td></tr>
<tr><td>3</td><td>Boat</td><td>To realize evolution in both various application and more efficient usage of energy sources through following stages:
1. Wooden log
2. Rowing boat
3. Sailing boat
4. Steam boat
5. Diesel boat
6. Jet boat
7. Atomic boat</td><td>
</td></tr>
<tr><td>4</td><td>Voice recorder</td><td>To realize evolution on quality of object through following stages:
1. Wax drum
2. Vinyl recording
3. Steel wire
4. Magnetic tape
5. Digital magnetic recording
6. Digital optical recording
* improving the technology</td><td>
</td></tr>
<tr><td>5</td><td>Coffee maker</td><td>To realize evolution on quality of object, adding necessary and complementary processes to the system, and co-ordination with super-system through following stages:
1. Pot
2. Pot with handle
3. Kettle to brew coffee with boiled water
4. Kettle to brew coffee with steam
5. Electrical coffee maker
6. Capsules of different tastes of coffee
7. Device for one cup of coffee
* bring available technology into the field</td><td></td></tr>
</table>

2. Characteristics of five patents related to cooling as the second form of stimulus for improving R&D engineer performances and skills in designing the next generation of technical systems

No.	Patents titles	Publishing date	Explanation
1	Blast furnace cold-intensifying and heat avoiding type gradient brick distribution method	Sep 2013	– Similar system related to temperature with different materials – far field – combination of simple systems * new materials, fields, …
2	Ice cream maker	Sep 2012	– Similar system related to cooling – System combined of 2 function of cooling and processing food simulta-neously – Systems before * adding necessary and complementary processes to the system * new application
3	Automated refrigerator opener	July 2012	– Family member/ industrial fridge – Related to sub-systems (improvements in sub-systems) – Related to less energy usage (hard-ware of technology) * convenience and smartness
4	Shelf life expiration date management	Nov 2012	– Family member/ industrial fridge – Related to sub-systems (improvements in sub-systems) – Related to smartness (software of technology instead of hardware) * convenience and smartness * consider quality of object
5	Customizable organizer assembly	Nov 2013	– Related to sub-systems (improvements in sub-systems) – Related to flexibility (hardware of technology) * to consider super-system * adaptation to real condition

3. Five-step procedure as the third form of stimulus for improving R&D engineer performances and skills in designing the next generation of technical systems

No.	Main concept and steps	Guidelines
1	Define the function of system	1.1. Define the duty of system in the desire situation; 1.2. Define the object which receives the duty of system; 1.3. Redefine the duty of system according to the requirements of the object; 1.4. Reformulate the defined duty according to the pattern: <verb> + <subject/noun> + <additives/object..>
2	Define the technical problems which are solved to deliver the function	2.1. Define time period which this function was delivered from the past (Time of emergence of the system/ time of demise of previous version of system); 2.2. Analyze more details in 2 following points of time: ▪ Think about Sub-systems and super-systems in present; ▪ Think about sub-systems and super-systems in past; 2.3. Find the problems which are solved in transition from past to present: ▪ In sub-system level (among sub-systems of past & sub-systems of present); ▪ In super-system level (among super-systems of past & super-systems of present);
3	Define technical problems in the form of contradiction	3.1. Analyze the problems: ▪ Which technical improvements are seen in the system (improving parameters)? ▪ Which barriers didn't let the system to improve more (worsening parameters)? ▪ So which parameters were against which parameters? 3.2. Check the presence of above contradictions in transition between present to future. ▪ Are the same technical improvements needed? ▪ Are the previous barriers still active in transition from present to future?
4	Analyze the applied solutions for the contradictions	4.1. What was the main component in resolving the contradiction in transition from past to present: ▪ In sub-system level; ▪ In super-system level; ▪ In systems around; 4.2. What are the main physical effect and main material in resolving the contradiction? ▪ In sub-system level; ▪ In super-system level; ▪ In systems around;
5	Propose new solution for the contradictions	5.1. Resolve contradiction in transition from present to future: ▪ In higher performance compare to the current system; ▪ By merging to the super-system (or systems around); ▪ By applying new physical effects even if it pushes to change the sub-systems and their materials.