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Engineering Idea Generation Framework for the Digital Era

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Abstract

Due to the lack of creative tools in engineering, graduated engineers have been reported to lack creativity. Engineering design processes provide structure for problem-solving but do not aim for novelty but rather explore than expand the known design space. Idea generation is a part of the engineering design, which is built on innovation theory. The mechanisms behind the myriad of idea generation tools have been also been identified in recent literature. Furthermore, computer aided innovation tools have emerged that offer effortless and efficient exploration of the design space. A unified framework is reconstructed here based on the recognized ideation mechanisms and computer aided innovation tools. The framework has typical stages, framing, ideation, selection and evaluation, yet the implementation and integration of the stages is novel. The proposed approach uses a semantic graph to frame the problem. Then, idea generation is done based on random and guided stimuli to generate high quantity of ideas. The best idea is selected based on pairwise ranking. Lastly, the idea is evaluated based on a function of the requirements it meets. The central aspects of the proposed framework are integration of computer aided innovation and idea generation tools, digitalization and automation of the process and its documentation.

Keywords: idea generation, engineering design, design methods

1 Introduction

Creativity and the ability to innovate have been shown to be crucial aspects for business growth and survival (T. J. Howard, Culley, & Dekoninck, 2008, 2009). However, creative ability has been perceived as something one is born with, rather than something you can learn and master (Olken, 1964). Creativity is commonly though of as a matter of thinking freely and without constrains, which is also perceived mainly as artistic activity (D. H. Cropley, 2015). Engineers have been reported to lack creativity still in 2010's (D. H. Cropley, 2015). One reason could be that the education system is too focused on content mastery. Creativity might not be discouraged but it is not particularly rewarded either. The relationship between knowledge and creativity is U-shaped. Both expertise and ignorance may inhibit the creative ability (Martinsen, 1995; Mumford & Gustafson, 1988). Thus, in addition to content mastery, engineers should also have modern and practical creative tools at their disposal to unlock their creative potential.

The ability to make remote associations has been shown to correlate with creative ability (Guilford, 1950; S. Mednick, 1962). Making associations stems from an individuals experiences and history. Associations can be verbal or visual but just as well based on feelings, smells and sounds. Everyone is creative in their own way but it is a skill to make associations. Some are better visualizers, others are more talented verbally (S. Mednick, 1962). Furthermore, diverse teams have more potential for creative output, because each person brings their own palette of associations based on personal experiences to the table (Van Knippenberg, Van Ginkel, & Homan, 2013). In this paper, a practical engineering creativity framework for the digital era is presented that applies association skills in engineering design. The framework consists of a framing tool for problem definition, an ideation tool for concept generation, and selection and evaluation tools for concept selection.

2 Background

2.1 History of Innovation Theory

Prindle (1906) was the first to propose to create a creative practice for engineers to create commercial products. He stated that the creativity of products lies in the association of known elements, which are combined in an unprecedented way. Wallas (1926) presented a creative mental process, which is similar to what was earlier proposed by the French Ribot (1908), consisting of four main phases: preparation, incubation, illumination and verification. Incubation is emphasized as an important step, in which one disengages from problem-solving, which helps in distancing one from obvious solutions and biases.

Osborn proposed the "Brainstorming" method of free thinking in 1952, which was highly promoted and lead to series of books (Olken, 1964; Osborn, 2011). Brainstorming is considered as a simple method but is therefore only meant for solving simple problems (Olken, 1964). According to Olken (1964), the creative process should be broken down to small inventive steps, in which the problem is tackled with minor advancements with systematic progress. Iteration is also key, as with each creative iteration more is learned about the problem (Rossman, 1931). Recent research has shown that in brainstorming the idea generation quantity slowly decreases after 30 minutes and the quality decreases drastically after 20 minutes (T. Howard, Culley, & Dekoninck, 2008). It has also been shown that introduction of stimuli to the brainstorming sessions improves the quantity and quality of generated ideas (T. J. Howard et al., 2009).

Guilford (1950) noted that consistently creative engineers were noted to be sensitive to even minor problems. They had an obsession to find out the root cause of any issues, even ones that others regarded as experimental errors or random phenomena. Another conclusion he had was that ideas and their potential are hard to evaluate at face value, and therefore a good strategy is to focus on quantity instead of quality because then the probability of landing a quality idea is higher. Guilford also noted that all the other steps in an engineering design process are convergent in nature except for concept generation, which is divergent. In other words, only the creative part of engineering design requires synthesis, while the other stages are based on analysis.

S. Mednick (1962) identified three ways for generating new solutions using association: serendipity, similarity and mediation. *Serendipity* refers to invention by accident, randomly, or even mistakenly, combining two or more things. *Similarity* is the association of ideas with the same goal, or the association between the ideas (homonym, rhyme, rhythm, etc.). Similarity is often seen in visual fields of arts and design, such as sculpting, illustrations and architecture. *Mediation* focuses on finding mediating links, which combine two or more things that are related. It is used to find common elements of things, ideas, factors, variables, parameters or theories, including the correlation of factors. Mediation is utilized in symbolic fields, such as math, physics, chemistry and engineering. Mednick also notes that the more remote the elements of an associative combination, the more creative the process or solution.

In addition to remote association, the source of creative superiority of a solution comes from the number requirements (primary and secondary) it meets. However, Mednick suggests that it is not purely the sum, but some function of the met requirements. Associative warm-up also increases creative productivity, especially if the warm-up stimuli are similar to task materials. This is also called associative priming, which has been shown to increase creativity. Since making associations can take time, time is not a factor influencing associative priming. (M. T. Mednick, Mednick, & Mednick, 1964)

The Geneplore model was proposed by Finke, Ward, and Smith (1992). It has two phases, generation and exploration, which are analogous with the notion of divergent and convergent thinking (Guilford, 1950; Pritzker & Runco, 2011). A. Cropley (2006) emphasized the need for convergent thinking as a part of the creative process. However, too much of it will lead to stagnated and routine solutions. The contradictory ways of divergent and convergent thinking are required in a creative process, which is referred to as the paradox of creativity (D. H. Cropley, 2016). A convergent, structured process can sometimes aid and at other times inhibit creativity. Sometimes an open and relaxed atmosphere is inspiring, sometimes inspiration is better fostered from the rebellious attitude towards an atmosphere that is strict and limiting. A creative process must therefore have a balance of order and chaos, freedom and constrains, knowledge and imagination (D. H. Cropley, 2015).

Recently, Kirjavainen and Hölttä-Otto (2021) investigated the underlying idea generating mechanisms behind known innovation techniques. They included 88 concept generation techniques in their analysis and suggested a framework consisting of 25 identified idea generation mechanisms. The identified idea generation mechanisms were associations, stimuli, incubation, building on others and analogies. The process mechanisms they found were aiming for quantity, combination, modification, classification, selection, evaluation, iteration, framing and suspending judgement. The aim here is to reconstruct a new idea generation framework based on these identified mechanisms.

2.2 Computer Aided Innovation

Computer aided innovation (CAI) is a research field, which aims to develop and research digital innovation tools to aid increase creative performance (Leon, 2009). CAI methods and tools are partly inspired by well-known innovation theories, including TRIZ, OTMS-TRIZ, ASIT, axiomatic design, synectics (Gordon, 1961), general theory of innovation (GTI) (Yezersky, 2007), mind mapping, brainstorming (Osborn, 2011), and lateral thinking (De Bono & Zimbalist, 1970). Semantic graphs can be used to computationally find semantic similarities of concepts (Zhong, Zhu, Li, & Yu, 2002).

Therefore, semantic graphs could be used as a tool in a creative process to aid in non-intuitive remote associations. Evolution theory has also been applied for CAI by combining genetic algorithms with computer aided design programs to come up with innovative 3D designs (Leon, 2009). However, applying genetic algorithms is case-specific whereas semantic graphs can be applied to engineering problem-solving in general.

Semantic graphs, or networks, are a way to store data in a form a web instead of typical key-value database. It is an interlinked data topology. Data are tied together with the use of semantic triplets. Semantic triplets are a technique used in *Natural Language Processing* (NLP), which is the combination of linguistics and machine learning. Semantic triplets consist of a subject, predicate and object, such as "food-is-good" and "dog-has-legs". These triplets are the working principle of Resource Description Framework (RDF), which is a standard for interlinked metadata, which is a human and machine readable format (Miller, 1998). Prominent open-source NLP tools include SpaCy, NLTK, StanfordNLP, OpenNLP and Gate. Of these tools, StanfordNLP works the best in most cases (Schmitt, Kubler, Robert, Papadakis, & LeTraon, 2019).

Semantic graphs can suggest associations based on verbal correlations using machine learning. In verbal associations, words can be encoded by their meanings as vectors of numbers. Word2vec is a neural network model that is made to interlink the associations between words in a text corpus (Mikolov, Chen, Corrado, & Dean, 2013). For example, in Word2vec the word "king" and "man" are associated stronger than "king" and "queen", but in a different dimension. In addition, not only word to word associations can be made but also between sentences and even between a word and a sentence.

A semantic graph can also be built manually, which resembles the creation of a mind map. The difference to an ordinary mind map is the links between things have the predicative, the expressive, property to them and that the semantic graph is constructed in a digital format. The expressive property, the predicative, can be associated to other contexts, such as biology and nature which are often the source of inspiration for technological advances.

2.3 Idea Generation Frameworks for Engineers

The most well-know practical framework for creating novel solutions is TRIZ. TRIZ is roughly translated as "the theory of inventive problem solving", which was invented and improved from the 1940s till the 1980s by Russian Genrikh Altshuller and his colleagues (Altshuller, 1999; Ilevbare, Probert, & Phaal, 2013). They investigated around 400,000 technology patents and based on them came up with 40 principles, 76 standard solutions and other approaches to creating new concepts. The idea of TRIZ is that innovations do not just happen by accident but can be invented with a systematic approach. TRIZ utilizes convergent thinking and analysis as opposed to the divergent free-form thinking of "Brainstorming". Given all the praise TRIZ has accordingly received, one thing it is lacking is a sequence of how to apply the tools (Eversheim, 2008). The abundant amount of information that TRIZ has can become too distracting or laboursome for the creative process. A survey showed that main benefits of using TRIZ are clear tools for creative problem solving and that it provides more novel concepts (Ilevbare et al., 2013).

However, the abundance of the TRIZ tools makes it difficult to implement, since no sequence is provided Eversheim (2008). Two ways have been suggested. The tools can be divided into analytical tools, knowledge-based tools and psychological operators (Zlotin et al., 2001). The first ones are used for problem definition, second for solution proposition and the last for facilitation the creative process. Another way to categorise the tools is by product centricity: current state, intended state, goals, transformation and resources (Moehrle, 2005). There are also many software available to carry out TRIZ (Spreafico & Russo, 2016). However, none of these software are as popular as TRIZ itself and suffer from the complexity.

Algorithm of inventive problems solving (ARIZ) is a TRIZ tool that provides a sequence of how to use TRIZ tools effectively to solve a technical problem. The most popular edition is ARIZ-85C, which contains nine steps, of which is contains several substeps and if-statements. TRIZ requires a lot of studying and practice before the tools are mastered and the framework can be used effectively. In practice, it has been observed that TRIZ suffers from problems related to the rigid and complex methodology, inordinate time requirement, lack of standards and best practices, organizational and cultural issues (Spreafico & Russo, 2016). In the survey, simplification of the methodology was given as the main feedback to improve its usability. However, efforts have been made to simplify and ease the use of TRIZ (Cameron, 2010; Gadd, 2011; Rantanen & Domb, 2002).

T. J. Howard et al. (2008) the theoretical integration of engineering design and cognitive psychology in order to propose a theoretical model for engineering creativity. They proposed a practical, software alternative to TRIZ, called Sweeper. Sweeper was shown to provide similar level of support to concept generation as TRIZ but it was much simpler. The idea of Sweeper is similar to TRIZ, in which links are created between the requirements of the current problem to random stimuli and previous projects in a company (T. J. Howard et al., 2009). The tool utilizes internet sources for stimuli as well. This associative priming is used with random and guided images from an external source (the internet) and also from an internal source (company's previous projects and ideation sessions). All stimuli were proven to be useful.

It was found that random stimuli from an external source was better for producing higher quality and quantity ideas compared to stimuli related to internal projects and ones that were related to this project by the requirements of the idea. Intermediate association stimuli has been observed to provide the best support for generating large number of ideas compared to very close or distant stimuli (Goncalves, Cardoso, & Badke-Schaub, 2013). These ideas were qualitatively estimated to be more creative in terms of fluency, flexibility and originality.

2.4 Research Gap

From an engineering perspective, the key to creativity is novel combinations of associative elements. Practical tools that support and nurture engineering creativity are vague and scarce. Especially digital tools on this front lack direction, sequence and guidance. One can utilize a digital whiteboard for co-innovation, but there is no structure or guidance to make a brainstorming session effective and fruitful, other than constraining from criticism and judgement of ideas. TRIZ is one of the few well-known engineering creativity tool. It focuses on the associations between solutions but the approach does not have a systematic sequence to apply them and suffers from overabundance of tools and information.

Based on the previous innovation theories, CAI and innovation generation frameworks it is clear that prominent tools and methods exists to support engineers in creative endeavours. However, these tools and methods seem to lack the following three aspects:

1. **Integration.** To the best of the Author's knowledge and the literature review, CAI has not been integrated with innovation theory methods before.
2. **Simplification.** The available digital tools (see (Spreafico & Russo, 2016)) are not simple because of the underlying complex innovation and TRIZ theory. It requires studying and practicing to master. The innovation theory foundations are formalized to explain and describe innovation, rather than providing support for the innovation process.
3. **Automation.** The documentation of idea generation is typically unorganized, unclear and laborious. The ideation process and its results should be automatically recorded in a standardized format. Based on the literature review, this is not implemented in the current idea generation software.

3 Proposed Framework

S. Mednick (1962) defines a creative tool as follows: "Any method, ability or habit that can be used to aid in linking remote ideas can be considered as a creative tool". Furthermore, an engineering creativity support tool should include one or more of the following: framing tool for problem definition, ideation tool for concept generation, and selection and evaluation tool for concept selection (T. J. Howard et al., 2009).

These aspects are the foundations of the proposed framework, which is presented in Figure 1. One vital property of the proposed methodology is that the tools are all in digital form, which enables the automatic generation of standardized documentation. The format of the documentation of the creative process and its outcomes is then always the same and eases then the interpretation and understanding - much like scientific articles. In addition a guided digital platform avoids distracting the creative problem-solving process compared to a pen-and-paper documentation.

Next, the three tools are presented in the context of autonomous robot delivery. Autonomous robot delivery can be carried out with any form of locomotion, such as flying, rolling, walking, but they all have their pros and cons. Traditional delivery systems include ships, planes and trucks. A creative solution for the future of autonomous package delivery is used as a toy problem to demonstrate the proposed creative tools.

3.1 Framing

The framing tool is based on semantic knowledge graphs. The interlinked topology of these graphs with the utilization of machine learning aided word associations gives an advantage over the abundance of information. Shared semantic conception of the task is vital, since it has been shown that there is significant difference on how a novice and an expert organize an engineering design problem mentally (Björklund, 2013). In contrast to the problem definition of the engineering design process, where the problem requirements and limitations are studied, the semantic framing aims to place the problem in a larger context, its links to the world and other similar problems. The creation of the semantic graph is done using machine learning techniques to collect and reformat data from

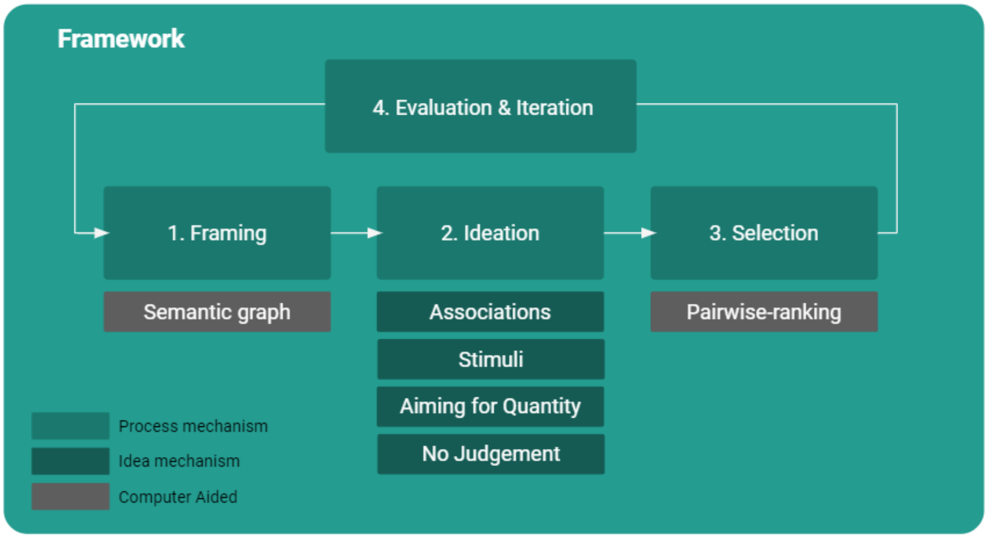

Figure 1: The proposed framework consisting of known ideation processes and mechanisms combined with computer aided tools. All parts of the framework are meant to be in a digital process and documentation of all actions is kept automatically.

the internet or a local system. An example semantic graph of a problem framing is shown in Figure 2.

3.2 Ideation

The ideation consist of warm-up and generation phases. Random and task-related stimuli are used to broaden the minds of the inventors to assist in remote associations. Intermediate association stimuli should be used, as it is better than close or remote stimuli (Goncalves et al., 2013). The problem at hand is ignored in the warm-up phase, which can be considered as "mental stretching" of the unconscious. These exercises are commonly used in improvisation theatre that not only prime the mind for associations but build trust and confidence within a group. The warm-up is carried

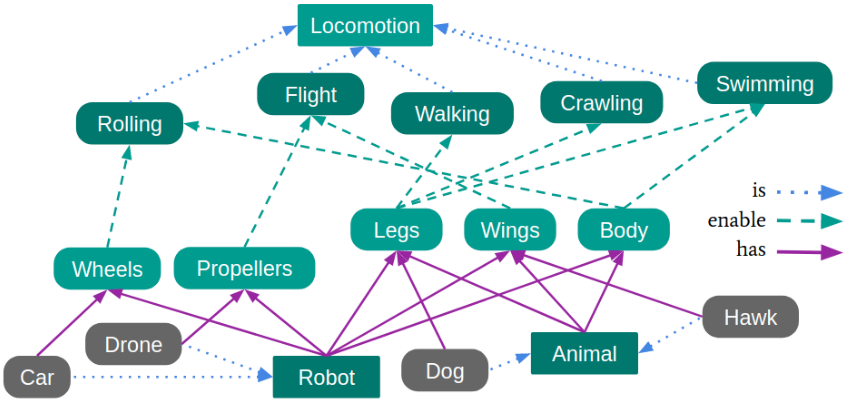

Figure 2: Semantic graph can be used to find associations through mediator variables.

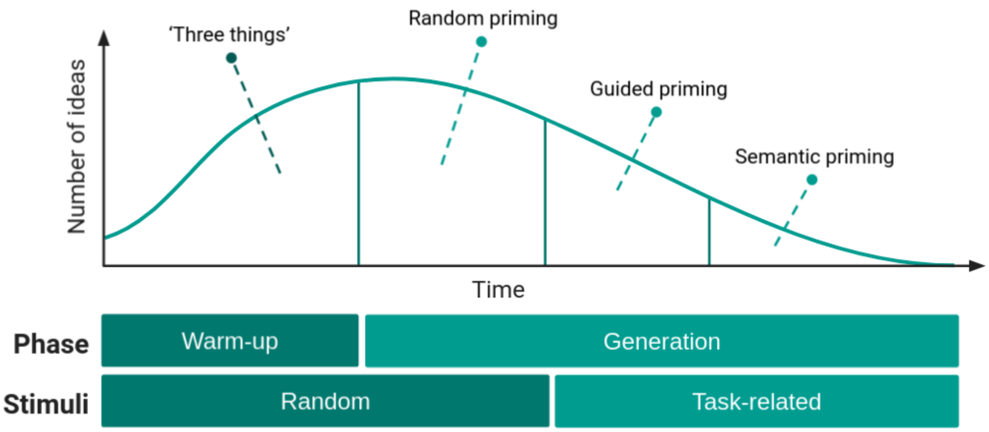

Figure 3: Ideation process, which begins with a warm-up, which is followed by idea generation.

out with a well-known improvising technique called "Three things". In this technique, or game, a person gives another person a random stimulus and based on the stimulus one has to generate three associations to the stimulus. For example, given the stimulus ’robot’ one might answer ’dance’, ’Star Wars’, ’Future’. The point of the exercise is not to judge nor aim for perfection but rather to prime the subconscious for associative work. The stimuli of the warm-up should be mainly random. The random stimuli can be either given by other group members or from provided by the software.

The concept generation is done with random, task-related and semantic priming. The generation phase starts with *random priming*, in which the ideators will generate ideas to solve the problem. Emphasis is on quantity of ideas, which can be very imaginary and far from reality. Each of the concepts are drawn and given a name, even if the person coming up with the concept does not have a fully comprehensive idea in mind. If the inventor of an idea cannot sketch the entire idea, then they will do so to the best of their ability.

Next, task-related stimuli is introduced in *guided priming*, which most likely reduces the quantity of ideas generated but increases the probability of higher creative quality. Lastly, *semantic priming* uses the semantic graph as a source. The semantic graph is then also updated if new insights provide more material to extend the graph. Ideation process is depicted in Figure 3 aims to first utilize diverse random stimulus to avoid stagnation and increase the quantity of ideas. If the ideas or any other stimuli during the concept generation are stagnated or revolve around few themes, it is unlikely to generate novel concepts compared to a situation where the ideas and stimuli are diverse (Perttula & Sipilä, 2007). In addition to verbal stimulation, visual and auditive stimulus should also be utilized.

3.3 Selection

People are poor at grading ideas on a scale, such as 1-5, but are better at comparing ideas. Pairwise conjoint analysis has been proven to be sufficient tool in difficult decision-making (Hansen & Ombler, 2009). Pairwise-raking resembles a tournament, where each solutions is compared against one another. Hansen and Ombler (2009) proposed a method for scoring alternatives by comparing them pairwise, which is a variant of conjoint analysis (Green & Srinivasan, 1978). The method is called *PAPRIKA* (Potentially All Pairwise RanKings of all possible Alternatives). In PAPRIKA, the minimum amount of pairwise comparisons are made in order to rank the alternatives from best to worst. This enables efficient time-use of the concept selection phase and anonymous participation of all of the attendees.

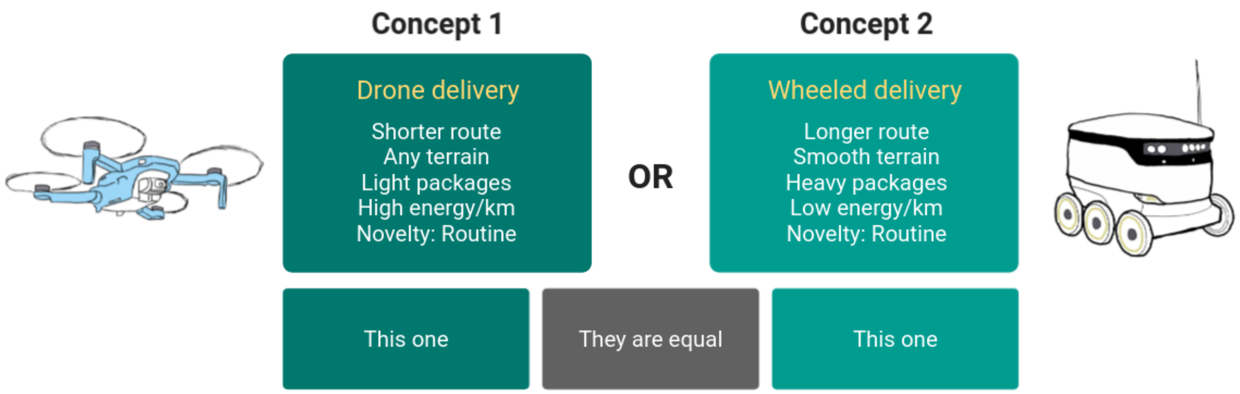

Figure 4: Robotic delivery locomotion comparison using pairwise conjoint analysis method. The illustrations are drawings of the DJI Mavic Mini drone and the Starship delivery robot.

Essential properties and comparison criteria are displayed when making the decision of which of two alternatives is preferred. PAPRIKA can be implemented in a digital format, such as the 1000minds program, which allows for the shared decision-making of a large group (Hansen & Ombler, 2009; Johnson et al., 2014). The pairwise ranking of PAPRIKA has been successfully used in the critical decision-making in hospitals, where doctors have had to decide which patient needs to be treated first (Hansen & Ombler, 2009). The PAPRIKA method relies on using critical properties of the alternatives for the comparison. Therefore, the estimated pros and cons of the generated concepts has to be done before the PAPRIKA method. One of the criteria should be novelty and others related to the requirements of the problem.

3.4 Evaluation

Lastly, an implemented solution has to be evaluated. It was found out in the literature review that only quantity of ideas can be used to measure the effectiveness of a idea generation tool during the ideation. In retrospective analysis novelty, variety and quality can also be considered (Shah, Smith, & Vargas-Hernandez, 2003). In TRIZ, the benefits of the solutions are summed and compared to an ideal solution (Altshuller, 1999). However, S. Mednick (1962) suggested that the evaluation criteria should form as a function of the met requirements. Primary and secondary requirements should have a different weight and some primary requirements can be more important then others. It is suggested here that the function for the evaluation of the solution criteria is proposed and updated after each iteration for the next because more knowledge is acquired of the problem on each iteration. For the first iteration, the evaluation is done based on the TRIZ principle, after which it is updated based on the observations of solution implementation. First iteration solution is evaluated with

$$S = \frac{\sum m_1^i + \sum m_2^i}{\sum r_1^i + \sum r_2^i}, \tag{1}$$

where S is the score of the solution, which measures the fit of the solution on a scale from 0 to 1, r_1^i is a set primary requirement and r_2^i is a set secondary requirement. The variables m_1^i is a met primary requirement and m_2^i is a met secondary requirement. In the following iterations, a function of the requirements is used for the evaluation of the solution:

$$S = \frac{f(m_1^1, m_1^2, \ldots m_1^n; m_2^1, m_2^2, \ldots m_2^n)}{f(r_1^1, r_1^2, \ldots r_1^n; r_2^1, r_2^2, \ldots r_2^n)} \tag{2}$$

4 Discussion

Some of the arguments made in this paper are assumptions rather than observations or deductions. Even though the basis of the arguments made and the frameworks presented are rooted in the literature, these may not aid in the actual creative process of engineers. The performance of the proposed engineering creativity tool should be measured with the metrics of novelty, variety, quantity and quality of ideas. Empirical research will follow, in which the theoretical foundation laid out in this study will be tested and verified. The fundamental challenge of proposing unified creative practices for engineers is two-fold.

One could argue that the idea of studying the creativity part of engineering design is not required. The engineering design process after all is built to conceive new ideas that blossom from an accurate problem definition and the acknowledgement of the existing solutions. However, if the engineering design process would provide satisfactory level of novelty, then there would be no complaints about engineers lacking creativity. Secondly, because of the paradox of creativity, any method that is used for creativity should not rely on too strict rules or documentation. The popularity of brainstorming comes from the feeling of freedom and low effort. Thus, any idea generation approach has to feel effortless even if it is guided or controlled.

5 Conclusions

From the literature three shortcomings of the current idea generation tools and approaches were identified: integration, simplicity and automation. Computer aided innovation methods should be integrated with classical innovation theory methods. These integrated approaches should be also intuitive and easy to use, as for the most popular creative framework, TRIZ, has a steep learning curve. Automation of the documentation of the idea generation was also identified as essential aspect for a creative framework for engineers.

A creative framework was proposed that could incorporates these requirements. The framework utilizes innovation mechanism identified from the literature in addition to semantic graph and pairwise-ranking methods, which can be classified as computer aided innovation methods. The framework proposed differs from the previous ones in the literature by integrating computer aided innovation with innovation theory, simplicity and the readiness to be deployed as a digital implementation that automatically documents each concept and step taken in a comprehensive way. The framework has the potential to enable consistent and novel idea generation in both an industry or academic setting. Further experimental research has to be conducted to prove the feasibility of the framework.

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