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USING CROWDS IN ENGINEERING DESIGN – TOWARDS A HOLISTIC FRAMEWORK

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Abstract

Product development organizations are increasingly using crowdsourcing for design-related activities such as idea generation and evaluation, and solving difficult problems. In order to effectively use crowdsourcing within engineering systems design, it is important to systematically design these initiatives by considering conflicting goals such as maximizing participation and the quality of outcomes within cost constraints. There is currently a lack of holistic frameworks that help design engineers in designing crowd-based initiatives, specifically, framing problems, choosing the right type of crowdsourcing mechanisms, and designing incentives. This paper is an attempt towards such a holistic framework which consists of three phases. The first phase involves selecting from the four classes of crowdsourcing initiatives. The second phase involves making structural, problem-related and evaluation decisions about the crowdsourcing initiative. The third phase involves designing appropriate reward structures. An analytical modeling framework based on the theory of contests is presented, followed by a discussion of specific issues related to engineering systems design.

Keywords: Crowdsourcing and Funding, Decision making, Open Innovation, Participatory design

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1 FRAME OF REFERENCE -- USING CROWDS IN DESIGN

During the past decade there has been a growing interest in open innovation (Chesbrough et al. 2006) techniques, particularly, using external crowds within the engineering design and innovation process. Organizations have leveraged crowds for different aspects of innovation, including idea generation, concept evaluation, understanding customer needs, solution of specific problems, and raising funds for the innovation. Dell and Procter & Gamble have created "Idea Storm" (Dell 2014) and "Connect and Develop" (Procter&Gamble 2009) respectively with the goal of gathering ideas from crowds for new products or improvement of existing products. Organizations such as InnoCentive help other companies in solving difficult problems by designing and executing crowdsourcing contests. Platforms such as Amazon Mechanical Turk facilitate the use of crowds in performing tasks that are difficult to automate, but are easy for humans to do (Amazon Mechanical Turk 2014). Platforms such as Kickstarter (KickStarter 2014) and GoFundMe (GoFundMe 2014) support innovators in raising funds to support their innovation. At the time of publication of this article, the estimated number of crowdsourcing/crowdfunding sites was over 2500 (Cowdsourcing 2014).

The benefits of crowdsourcing are attributed to the "wisdom of the crowds" and parallel search by multiple people. While there is clear evidence of the benefits of using crowds in design, it is also known that not all crowdsourcing contests are equally effective or successful. There are many ways in which crowdsourcing initiatives may fail. An example of such failure is an initiative that fails to attract a crowd with a suitable number of participants with diverse expertise who submit good sets of ideas, both in quantity and variety. A crowdsourcing initiative may also fail if, for a similar expected outcome, the cost of executing it is greater than the cost of directly hiring experts. The cost of a crowdsourcing initiative consists of various components including the cost of designing and executing the initiative, the cost of filtering ideas from the crowd, etc. It is imperative to carefully design crowdsourcing initiatives to minimize the likelihood of failure.

Research on crowdsourcing is being carried by various research communities including information systems, management science, and computer science. A detailed review of crowdsourcing research was provided by Pedersen and co-authors (Pedersen et al. 2013). Recently, the engineering design research community has also worked on certain aspects of crowdsourcing to understand how it can be effectively used for engineering design. Gerth and co-authors discuss how crowdsourcing can be used in systems design (Gerth et al. 2012). The authors address a number of commonly raised concerns and discuss the advantages and disadvantages of using crowds for evaluating design ideas. They argue that advanced crowdsourcing mechanisms are needed in order to utilize crowdsourcing for complex systems design problems.

Designing crowdsourcing mechanisms requires a good understanding of the complex relationships among incentive structures, knowledge and expertise of participants, task characteristics, and the quality of outcomes. Crowdsourcing initiatives can be designed in different ways, and each initiative has a different level of effectiveness. For example, in design evaluation and idea generation activities using Amazon Mechanical Turk, each participant gets paid equally, whereas in other crowdsourcing competitions, only the selected winners get paid. Ideally, engineering designers must choose the best format for the task at hand. However, there is a lack of rigorous frameworks that support decisions related to the design of crowdsourcing initiatives for engineering systems design.

In this paper, we present a step towards addressing this research gap by presenting a game-theoretic framework to facilitate the design of crowdsourcing initiatives for engineering design. The framework allows designers to conceptually model the crowdsourcing process from a holistic viewpoint, and to quantitatively model the effects of different design decisions and incentive structures. The proposed framework for using crowdsourcing in design is presented in Section 2. An analytical framework to help in understanding the impacts of the design of crowdsourcing initiative is presented in Section 3. The analytical framework is based on the theory of contests, which a part of game theory. Finally, issues specific to engineering design problems are discussed in Section 4.

2 A FRAMEWORK FOR CROWDSOURCING IN ENGINEERING DESIGN

A framework for using crowdsourcing in engineering systems design is shown in Figure 1. The framework consists of three phases: 1) selecting a class of initiatives, 2) making various structural, problem-related and evaluation decisions about the initiative, and 3) designing an appropriate incentive structure. The details of the three phases are discussed next.

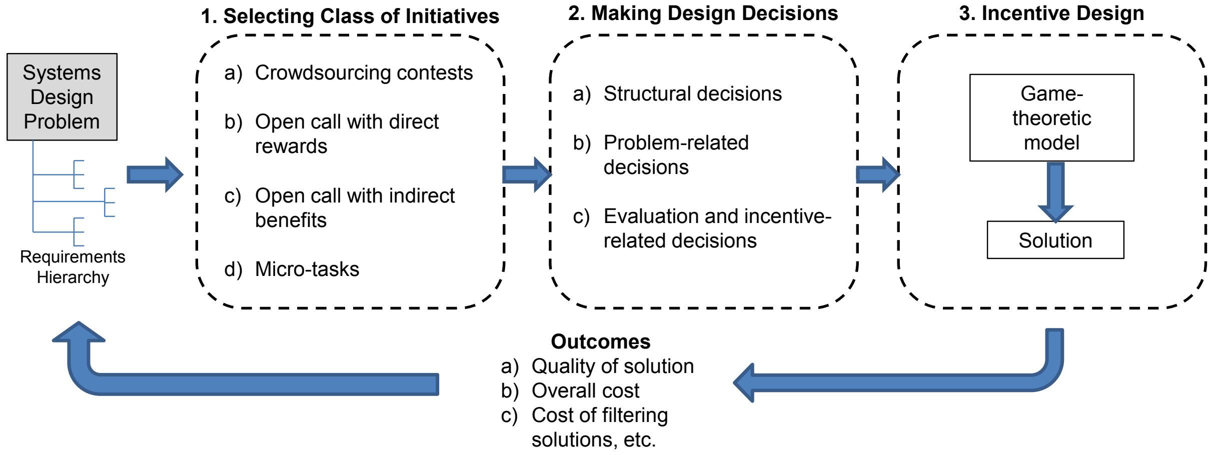

Figure 1. An illustration of the proposed framework for designing crowdsourcing initiatives for engineering design

2.1 Selecting the Class of Crowdsourcing Initiatives

As alluded to in Section 1, crowdsourcing has been used in different ways, and there are multiple ways in which the activities can be classified. Based on the type of the task, and the incentive structure, such initiatives can be broadly classified into (i) crowdsourcing contests, (ii) open calls with direct rewards, (iii) open call with indirect benefits, and (iv) micro-tasks.

1. *Crowdsourcing contests*: In these initiatives, a contest designer poses challenge problems for the crowd. The challenge problems are well-bounded, metrics for assessing the quality of the solutions are available, and the prize amounts for the winning entries are clearly defined. Individuals from the crowd respond to the challenge problems by submitting their solutions. Based on the quality of the proposed solutions, the prize winners are determined.
2. *Open calls with direct rewards*: In contrast to contests, the tasks in this class are broader and the quality measures are not clearly defined and provided to the participants. An example is the open call for ideas by Freudenberg's IdeaTrophy (Freudenberg 2014). Other examples include firms that create idea markets, e.g., Quirky (Quirky 2014). The ideas are either judged by a panel or through voting by the crowd. The individuals who submit the best ideas get financial rewards in the form of either cash prizes or royalties.
3. *Open calls with indirect benefits*: Dell IdeaStorm is an example where contributors are not rewarded financially. Instead, contributors benefit indirectly from the company's implementation of the ideas in their products (Huang et al. 2014). The contributors of the ideas also receive personal satisfaction if their idea is chosen for implementation by the firm. At the same time, the company benefits by gaining a better understanding of the customers' needs and preferences.
4. *Micro-tasks*: Micro-tasks are also referred to as Human Intelligence Tasks (HITs), which are easy for humans to accomplish but are difficult to automate on a computer. Examples of such tasks include tagging images with names of items in it, assessing the quality of images or ideas, and data cleaning and verification. In such crowdsourcing initiatives, everyone gets compensated equally for performing the task. An example of platforms that facilitate using crowds for HITs is the Amazon Mechanical Turk (Amazon Mechanical Turk 2014).

All these classes of initiatives are valuable within the engineering design process. Existing studies show the use of all the four classes of crowdsourcing initiatives in the design process. Crowdsourcing contests have been used by organizations such as DARPA (DARPA 2013) for systems design problems. In the Fast Adaptable Next-Generation Ground Vehicle (FANG) Mobility/Drivetrain Challenge, where the prize amount was $1 Million, the performance space was well defined and the performance criteria were clearly defined. Open calls associated with both direct and indirect rewards are particularly useful in the initial stages of design to help in understanding customer needs and to support concept generation. Finally, micro-tasks have primarily been used for evaluation of concepts and ideas in the form of product sketches. Kudrowitz and Wallace use Amazon Mechanical Turk to evaluate large numbers of product sketches (Kudrowitz and Wallace 2013). Green and co-authors use student subjects to crowdsource the task of evaluating creativity of solutions of design problems (Green et al. 2014). Their results suggest that it is possible for non-experts to evaluate the originality of ideas in a reliable manner, highlighting the benefit of using the wisdom of crowds in design.

2.2 Making Design Decisions about the Chosen Crowdsourcing Initiative

The second phase in the design of crowdsourcing initiatives involves making a number of decisions about the initiative. Some of the important decisions, which have a significant impact on the outcomes of the initiative, include deciding the duration of the activity, the number of stages in which the initiative would be performed, deciding who can participate, how the problem should be framed, how to choose the award recipients, how much reward should be given to different awardees, whether to allow team formation or not, and if teams are allowed, how should the rewards be distributed among team members. These decisions can be classified into structural decisions, problem-related decisions and evaluation and incentive-related decisions.

Structural decisions

- *Number of stages*: Crowdsourcing contests can either be designed as a single stage contest or a multi-stage contest. In single-stage contests, the winners are decided based on a single set of contributions. In contrast, in a two-stage contest, the set of participants is filtered, and a subset of the participants is allowed to participate in the second stage. The winners are decided based on the results of the second stage. Similarly, multi-stage contests can be designed.
- *Duration*: The duration of a contest has an effect on the quality of the solutions received. Crowdsourcing contests can range from a few hours to multiple weeks.
- *Restrictions to entry*: Participation in crowdsourcing initiatives can be restricted based on age, expertise, geographical location, etc. If there are no restrictions, it is called "open entry". To ensure that only dedicated individuals participate in the contest, an entry fee can be imposed.
- *Team formation*: If team formation is allowed, individuals can self-organize into teams and compete with other such teams.

Problem-related decisions

- *System decomposition*: Engineering systems design problems can be crowdsourced at different levels. The design of an entire system can either be crowdsourced in a grand competition or the system can be decomposed into subsystems, and multiple smaller competitions can be set up for the subsystems. If the systems design problem is partitioned into smaller competitions, different coordination schemes can be used for information exchange across competitions. The sequence of competitions can also be varied. All these decisions affect the final solution quality.
- *Information shared*: The amount of problem-related information to be shared with the contestants affects the expected quality and diversity of solutions. Hence, it must be decided carefully.

Evaluation and incentive-related decisions

- *Quality assessment*: The quality of the solutions can be assessed in different ways - through a pre-specified rating scale, by leveraging the crowd to vote on ideas, using experts to rate the ideas, or through a combination of these mechanisms.
- *Choice of winners*: After quality assessment, the contest designers must select and reward the winners. The reward structure can be set up as a winner-takes-all contest or as a multiple prize contest. The prize amount can either be fixed at the beginning of the contest or based on the quality of each submission.
- *Award distribution*: In the case of contests where teams are allowed, the mechanisms for distribution of the award among team members must be specified, e.g., uniform distribution,

distribution based on individual contributions, or any other distribution plan agreed upon by the team members.

2.3 Considerations in Designing Appropriate Incentives

The third phase in the design of crowdsourcing contests is the design of right extrinsic and intrinsic incentives to ensure successful outcomes. These contest design options discussed in Sections 2.1 and 2.2 have direct influence on the outcomes of a tournament. From the perspective of a tournament designer, the success of the initiative can be quantified in terms of factors such as:

- the quality of the solution to the challenge problem,
- the number of contributors,
- the amount of effort invested by the contestants,
- the quality of teams formed,
- the overall cost of running the contest,
- the probability of getting a good solution, and
- the cost of filtering good solutions.

After receiving the solutions from the crowd, the next step is to filter or synthesize the collective input. The cost of filtering ideas is an important aspect of the overall cost, and influences the effectiveness of the initiative. Note that the individuals' inputs depend on their payoffs, which depend on the design of the contest. Therefore, appropriately designed incentive structures can reduce the filtering cost and eliminate spammers (Raykar and Yu 2012).

In addition to modelling the effectiveness from the perspective of the designer, the effectiveness must also be considered from the perspective of the contestants. Benefits to the participants are dependent on the probability of winning a prize, the amount of effort involved, the prize amount, and any indirect (non-financial) benefits. If the participants do not benefit from their contribution, either directly or indirectly, then they would not be motivated to contribute in the future. Therefore, the initiative must be beneficial both for the organization and the participants to ensure its sustainability over time.

In summary, the key question faced by the crowdsourcing initiative designers is: which type of crowdsourcing contest to start, how to design a crowdsourcing contest, and how to design incentives. There is a need for an analytical framework to answer these questions. One such analytical framework is presented in the following section.

3 ANALYTICAL FRAMEWORK FOR CROWDSOURCING INITIATIVES

The analytical framework presented in this section is based on the theory of contests (Corchón 2007), which is a part of game theory. Game theoretic models have been used previously to model simple crowdsourcing contests. In this section, a brief overview of the models that can be used to analyse crowdsourcing contests is provided, followed by avenues for future research towards addressing the nuances of systems design problems.

3.1 Models of Crowdsourcing Contests

A contest is modelled as a non-cooperative game between N utility maximizing self-interested contestants. Assume a single-prize contest, where the prize amount is Π. The contestant who submits the solution with the best quality wins the prize. The expected payoff of i^{th} contestant, denoted by π_i, is dependent on the prize amount, Π, and the probability of winning the prize, P_i. The winning probability depends on the solution quality from all the participants. For example, considering all other factors to be uniform, the probability of winning is low if other participants submit solutions with higher quality, whereas the winning probability is high if the quality from other participants is lower. The solution quality is in turn dependent on the *participant characteristics*, such as the expertise, and *inputs* such as effort and time investment. Within a non-cooperative game formulation of a contest, the players decide on the *inputs,* such as how much effort and time to invest in order to maximize the expected payoff, π_i.

To determine the optimal strategies for each contestant, there is a need to quantify how the participants' inputs affect the solution quality, how the solution quality affects the winning probability, and how the winning probability affects the expected payoff. Therefore, a contest model involves specifying three functions: quality functions, contest success functions, and payoff functions (Corchón 2007). *Quality functions*, $q_i = q_i(e_i, E_i)$, quantify the solution quality (q_i) from contestants, as a function of the participant characteristics, such as expertise (e_i) and the inputs, such as effort (E_i). Here, quality is defined broadly to include all the attributes used in selecting the winner. These include performance of the solution, innovativeness, robustness, reliability, cost effectiveness, etc.

Contest success functions quantify the contestants' winning probability in terms of the quality of all solutions (Skaperdas 1996), $P_i = P_i(q_1, q_2, \ldots, q_N)$. The commonly used functional form of contest success functions is:

$$P_i = \begin{cases} \dfrac{f(q_i)}{\sum_{j=1}^{N} f(q_j)} & \text{if } \sum_{j=1}^{N} f(q_j) > 0 \\ \dfrac{1}{2} & \text{otherwise} \end{cases} \tag{1}$$

where $f(q_i)$ is an increasing non-negative function. Two commonly used functional forms of $f(q_i)$ are the *power form* and the *logit form*. The power form, $f(q_i) = q_i^m$, with $m > 0$, results in a contest success function of the form: $P_i = \dfrac{q_i^m}{\sum_{j=1}^{N} q_j^m}$. For a two-player scenario, $P_1 = \dfrac{q_1^m}{q_1^m + q_2^m} = \dfrac{1}{1 + \left(\dfrac{q_2}{q_1}\right)^m}$. Here, the probability of winning is dependent on the ratio of the quality of the submitted solutions. The logit form, $f(q_i) = e^{kq_i}$ with $k > 0$, results in the following contest success function: $P_i = \dfrac{e^{kq_i}}{\sum_{j=1}^{N} e^{kq_j}}$. For two players, this reduces to $P_1 = \dfrac{1}{1 + e^{k(q_2 - q_1)}}$. In this case, the probability of winning depends on the difference in the quality of the submitted solutions, $(q_2 - q_1)$.

Finally, the *payoff functions* relate the contest-specific design variables (e.g., the prize amount) to the individual payoffs. In a winner-takes-all contest, the payoff of an individual can be defined as the expected value of the prize, $E(\pi_i) = \Pi P_i - C_i$, where C_i is the cost incurred by the i^{th} contestant in developing the solution.

With the quality functions, contest success functions, and the payoff functions, the formulation of the non-cooperative game is complete. The solution of the game refers to the set of strategies that the contestants' are expected to adopt. Generally, the Nash equilibrium of the game is used as the solution. At the Nash equilibrium, no participant has an incentive to unilaterally deviate from their strategies. The strategies maximize the payoffs for each contestant, given that the strategies of other contestants are fixed. Sha et al. (Sha et al. 2014) show that if there are two contestants, the contest success function has the power form, the quality function is linear in effort, $q_i = \alpha E_i$, and the costs are uniform across participants ($C_i = C$), then the Nash equilibrium strategies are given by $E_i = \dfrac{\Pi m}{4C}$.

Such game theoretic models help in understanding the conflicting effects of variables such as the prize amount. A higher prize amount results in a higher expected payoff π_i for each contestant. However, it also results in a greater number of contestants, which reduces the winning probability for each contestant, thereby reducing the effort invested by each participant. Fullerton and McAfee show that the optimal number of contestants is two (Fullerton and McAfee 1999). Any further increase in the number of participants results in a lower effort by participants in equilibrium, and hence, a lower quality of the solution. This result is based on the assumption that each participant has identical expertise. If participants have different expertise, and diversity in solutions is important, higher number of participants is preferred.

Similar models have been developed for other types of mechanisms such as multiple winner contests and contestant selection auctions. The analytical framework based on contest theory can be used to quantify the effects of different tournament design concepts on the equilibrium effort invested by the players as a function of the exogenous parameters such as the prize, endogenous parameters such as the expertise and effort, and the structure of the game, such as winner-takes-all or auction style. While the model presented above is for a specific type of tasks where the quality is determined by the effort, the framework itself is highly general, and can be adapted to different types of tasks. Terwiesch and Xu (Terwiesch and Xu 2008) present three types of tasks: expertise-based, ideation-based, and trial-and-error projects. Each type of task has different types of uncertainty, and a different relationship between participant effort and the project outcome. The authors show the importance of considering the type of the task while creating the contest model.

3.2 Models of Crowdsourcing Contests with Team Formation

For simple tasks, crowdsourcing contests generally involve competition among individuals. However, as the tasks become more complex, the expertise of multiple individuals may be required to accomplish them. For example, in the DARPA drivetrain challenge (DARPA 2013), individuals were allowed to form teams and propose a "purse distribution plan" before submitting the solutions. If the individuals are allowed to (a) self-select their teams from the available set of contestants and (b) develop their own prize distribution plan, additional complexities arise in the analytical framework. An individual who is competing alone may be able to increase the probability of winning by partnering with another individual with complementary knowledge or expertise. But at the same time, the prize money gets distributed among multiple people, thereby reducing his/her expected payoff. Therefore, the analytical framework needs to be modified to account for such trade-offs.

A promising approach to address team formation within contests is the framework of *endogenous coalition formation for tournaments,* which is an extension of contest theory. In this framework, a generalized contest success function is developed to determine the probability of winning of a team, given the composition of other teams. Skaperdas (Skaperdas 1998) presents an extension to three players. The author assumes that the team members "pool their inputs" and contest against the other teams. Hence, if players p_1 and p_2 team up against player p_3, the team's probability of success (P_{1-2}) is: $P_{1-2} = \dfrac{f(q_{1-2}(e_1+e_2, E_1+E_2))}{f(q_{1-2}(e_1+e_2, E_1+E_2)) + f(q_3(e_3, E_3))}$, and the probability of success for the player p_3 is: $P_3 = \dfrac{f(q_3(e_3, E_3))}{f(q_{1-2}(e_1+e_2, E_1+E_2)) + f(q_3(e_3, E_3))}$. Here, Skaperdas assumes that the quality function remains the same as for individual contestants, the effort and expertise are both additive in nature, and the inputs of the teams are equal to the sum of inputs of individuals, representing resource pooling (Skaperdas 1998).

To determine the payoff for each individual within a team, a prize distribution plan is required. Skaperdas (Skaperdas 1998) assumes that after a team wins the contest, the members of the team participate in a second contest among the team members. The individual payoffs are proportional to the probability of winning of the team members in the second contest. For example, if the team with players p_1 and p_2 win the first contest, then the prize amount is distributed between p_1 and p_2

according to probabilities: $P_1^{(2)} = \dfrac{f(q_1(e_1, E_1))}{f(q_1(e_1, E_1)) + f(q_2(e_2, E_2))}$ and $P_2^{(2)} = \dfrac{f(q_2(e_2, E_2))}{f(q_1(e_1, E_1)) + f(q_2(e_2, E_2))}$ respectively. Therefore, the overall expected payoffs for the three players are: $E(\pi_1) = \Pi(P_{1-2}P_1^{(2)}) - C_1$, $E(\pi_2) = \Pi(P_{1-2}P_2^{(2)}) - C_2$, and $E(\pi_3) = \Pi(P_3) - C_3$ respectively. Using these expected payoffs, the stability of teams and the equilibrium efforts can be calculated.

The primary advantage of this approach is that it accounts for the team formation, prize distribution and the contest in a unified framework. It also considers inter-coalitional interactions, which are ignored in cooperative games.

3.3 Special Cases

The analytical framework discussed in Sections 3.1 and 3.2 is generally applicable to the four types of crowdsourcing initiatives discussed in Section 2.1. However, the models need to be particularized for specific initiatives. Consider the case where everyone gets compensated equally for their contributions. In this case, the probability of winning, P_i, is 1 for each individual. Therefore, the expected payoff for each individual is simply equal to $E(\pi_i) = \Pi - C_i$. The problem reduces from a game to a simple decision making problem where each individual independently decides whether to contribute or not based on individual costs. If the expected payoff is positive, an individual should participate in the activity. Such a model is applicable to *microtasks* such as tagging images, assessing quality of concepts, and data cleaning. In engineering design, such tasks include concept generation and idea evaluation. In each of these tasks, the effort required by the individuals is very low. In order to encourage participation, the designers of such initiatives only need to ensure that the amount paid to an individual, Π, is greater than the individual's cost, which may be different for each person. Alternatively, for a given problem, the model indicates that the participants would only submit solutions that are generated at a cost lower than Π. Hence, if the amount paid is low, there is a likelihood of getting large numbers of low-quality ideas, which may increase the cost of filtering them.

In the case of crowdsourcing initiatives where none of the participants receive any direct financial rewards, $\Pi = 0$. The expected payoff for each participant can be written as $E(\pi_i) = -C_i$. Therefore, if we only focus on the financial benefits, none of the individuals would participate. However, individuals receive indirect benefits from participating in such initiatives. In their analysis of participation in Dell IdeaStorm, Huang and co-authors argue that various non-financial factors play a role in participation decisions, including, personal benefit from the implementation of contributed ideas and social reputation (Huang et al. 2014). Similarly, the cost broadly includes cognitive effort and discontent when the firm does not respond to the suggestions from the contributors.

3.4 Extensions for Engineering Design Problems

The overall framework discussed in Section 3 can be used for designing crowdsourcing initiatives for design. The analytical models are simple and address some of the basic characteristics of design problems. To support the decisions listed in Section 2.2 for engineering design specific issues, the models need to be extended along different dimensions. For example, the process of design involves a variety of activities such as problem formulation, concept generation, analysis, experimentation, synthesis. Different design problems also have unique characteristics, e.g., original design is different from adaptive or variant design. Different design activities require different types of capabilities/inputs from the designers, and have different types of influence on the quality of the final outcome. Simple activities such as converting a CAD file into another format require the knowledge of the tools that provide such a capability. In such cases, the quality of the outcome is only dependent on the knowledge, the availability of the tool, and the corresponding effort involved. On the other hand, novel design activities require experimentation with different options and prototyping. In such novel activities, there is significant uncertainty and the quality of the final solution is dependent on the amount of experimentation. Hence, the quality function for such activities must account for the inherent uncertainty. This requires the development of different types of quality functions for modelling different design activities.

In addition to the diversity of design activities, systems design tasks are also complex in nature. The commonly used approach to managing complexity is problem decomposition (Simon 1962). Current models of contests do not address the hierarchical nature of problems. Additionally, design activities require expertise in multiple domains. For example, an electromechanical systems design problem requires expertise in thermal analysis, structural analysis, electrical systems, reliability assessment, etc. Hence, there is a need for establishing new quality functions and contest success functions to account for the impact of diverse expertise on the probability of success. Such extensions are avenues for further development of the analytical framework.

4 DISCUSSION

Crowdsourcing is an active area of research within various communities ranging from management science to computer science, each community focusing on different aspects. To make rapid progress in using crowds for engineering systems design, it is important to leverage research from other domains, while concurrently addressing challenges that are unique to design problems. One such challenge is the complexity of the design problems, which results in interdependencies among different activities. Existing research in crowdsourcing is mainly focused on individual tasks. Addressing interactions between different aspects of designs in the use of crowds is an open research issue.

Another challenge in design problems arises from the complexity of human decision making. Analytical models of decision making, such as those presented in Sections 3.1 and 3.2, are based on certain assumptions about rationality and information availability. It is well known that humans deviate from such idealized models because of information processing limitations. Therefore, it is important to first understand the effects of such assumptions on the outcomes, and then to account for the deviations from rationality for more accurate models. One way to understand such deviations is through behavioural experimentation. Sha and co-authors have taken a step in this direction by using behavioural experiments to validate simple models of design crowdsourcing based on contest theory (Sha et al. 2014). The authors validate the outcomes of a contest model using a simple optimization problem as a representative design problem, and set up computer games played by human subjects. Other research challenges include the presence of (i) networks of decisions in design processes, and (ii) learning effects along a design process.

There are also challenges associated with integrating existing systems engineering practices with crowd-based processes. Organizations deciding how to use crowdsourcing in systems engineering processes, must decide what information they are willing to reveal about their problems, because the information may reveal the organization's strategies to their competitors. Organizations must decide how to partition problems into sub-problems that can be crowdsourced and sub-problems that must be solved in house. There is an analogous issue from the perspective of the individual contestants also. In order to respond to a contest, individuals must completely reveal their design (and intellectual property) to the organization. This poses a significant barrier to using crowdsourcing in design.

Crowdsourcing in design can be viewed as an economic transaction in information. Information as an economic good has some unique properties (Bates 1990) - generation of information is costly, but if someone receives the information, its marginal cost of reproduction is almost zero. Therefore, confidentiality plays an extremely important role in using crowds in design. Foundational techniques are needed to preserve confidentiality in design. Wang and co-authors present a set of protocols to enable integrated simulation of two subsystems without requiring the two designers to reveal subsystem information to each other (Wang et al. 2014). Similar approaches that allow evaluating design concepts without revealing detailed design information can greatly reduce the barrier in using crowdsourcing as a core strategy in product development, and can improve the participation of individuals in design crowdsourcing.

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