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Applying Systems Engineering to Survey Research

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Abstract

As systems engineering research matures, empirical data collection methods, such as surveys, are expected to be increasingly applied. Survey research has the potential to advance the maturity of systems engineering research. Applying systems engineering to survey research also has the potential to enhance survey research by offering a perspective that can improve the performance of various survey related activities. The authors' experiences with a case study survey are examined in the context of systems engineering technical and management processes, methods and tools. The current state of survey research literature is examined, and recommendations for how systems engineering can improve survey research are discussed. These recommendations include: (1) perform an in-depth analysis of the requirements of all of the stakeholders of the survey and (2) leverage the framework of risk and opportunity management offered by systems engineering to address survey data threats to validity. Researchers from all fields who use surveys to collect data can benefit from this complementary perspective and the unique recommendations presented in this paper.

Keywords: Systems Engineering Surveys; Systems Engineering Empirical Research, Survey Research

1. The Relationship between Survey Research and Systems Engineering

As systems engineering matures as a field, there is a need to advance empirical research in systems engineering [1]. Multiple empirical data collection methods can be used in systems engineering research including interviews, experiments and surveys. Surveys have distinct advantages for certain types of data collection. Surveys can obtain data from a significant number of respondents who are geographically dispersed at a reasonable cost. In recent years, there are a growing number of systems engineering research studies that employ surveys to collect data. Examples of these include a study to understand the effects of the application of systems engineering best practices on project performance [2], a study to build a business case for systems engineering [3], a study to evaluate the importance of various lean enablers for systems engineering [4], a study to determine the role of the product domain and the project domain in systems engineering management [5], a study to select elements of systems engineering

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that are important for upgrading legacy systems [6] and a study to understand how project management teams manage requirements [7].

In addition to surveys being used to advance systems engineering, systems engineering can also be used to advance survey research. Systems engineering offers a perspective that can be used to improve the best practices related to various survey research activities documented in the survey literature. Systems engineering also offers processes, methods and tools that can support effective survey research. While the applicability of systems engineering to derive survey questions has been explored [8], systems engineering has the potential to improve the effectiveness of the entire survey lifecycle.

The survey lifecycle encompasses processes from the time that a decision is made to use survey methods until the data from the survey has been thoroughly analyzed and results have been disseminated. The survey lifecycle includes determining the data items that need to be collected to address the research hypotheses, formulating questions to elicit the data items, reviewing and verifying the survey questions, implementing the survey (e.g., creating a questionnaire form to be mailed out, coding the survey online), verifying and validating the survey instrument, conducting the survey, managing and analyzing the survey data and ensuring that the necessary parties have the data and results from the survey.

This paper focuses on how to use systems engineering to organize and guide survey research. The authors' experiences with a case study survey are examined in the context of systems engineering technical and management processes. Specifically, the following processes are discussed in the context of survey research: stakeholder requirements analysis, architecture design, implementation, validation, verification, project planning, risk and opportunity management, and information management. Methods and tools are also discussed in the context of these systems engineering processes. Specific recommendations are offered in the conclusions related to how systems engineering can improve survey research.

2. Background

This section provides background information about the authors' survey and a brief overview of existing survey research.

2.1. Case Study: The Survey to Assess the Relationships Between Systems Engineering Factors and Proposal Success

Mastering the proposal process is a key survival skill for organizations that thrive on contract work. Proposals are often paid for out of precious company overhead. Failure to win enough contracts can exhaust a company's resources and drive the company out of business. Systems engineering is needed to support proposals when complex systems are being engineered. Often for complex systems, there is a need for technical expertise to align contract opportunities with an organization's technical competencies, to define the solution to be proposed and to estimate the costs related to a proposed solution [9]. The authors are determining an optimal use of systems engineering in support of the proposal process as part of doctoral research. The authors are conducting a survey to gather data to allow a number of candidate predictors of proposal success to be evaluated. This survey case study will be analyzed in the context of systems engineering processes.

2.2. Existing Survey Research Literature

An extensive body of literature exists related to survey research methods that individuals conducting surveys can draw from. Most of this literature provides guidance for a number of activities that must be undertaken as part of survey research. For example, literature exists for determining whether, for a particular type of data collection effort, respondents should fill out a questionnaire given just written directions or whether interviewers should be involved in interfacing with respondents and coding responses [10-12]. For questionnaire research, some sources help guide decision making regarding whether a physical copy of the questionnaire should be supplied to respondents or whether respondents should fill out the survey via the internet [13,14]. A number of sources provide guidance for selecting the sample of people to target as potential survey respondents [10,11,15] and provide guidance for effective question writing [10,12,16]. Once the questions are composed, there is literature that offers

guidance for how to administer surveys [10-12,17] and how to prepare the survey data for analysis [12].

Much of the literature addresses multiple activities and topics in survey research. Some literature discusses survey research in the context of research design philosophy [18]. Other literature provides guidance related to particular aspects of managing surveys such as how to organize a team of people conducting a survey [19], how to plan resources to support a survey [19] and how to avoid common survey management "pitfalls" [20]. As a whole, the majority of the literature addresses survey research as a number of disparate activities or topics and then provides guidance related to each of those activities or topics. The survey methods literature could benefit from a broader perspective, such as that potentially offered by systems engineering.

3. Applying Systems Engineering to Survey Research

Systems engineering provides a framework that can organize and guide creative problem solving from the definition of customer needs up through the corresponding solution. As a result, systems engineering is sometimes applied in novel ways to address novel problems. For example, researchers have applied systems engineering to computational biology problems [21] and to management problems for coastal maritime traffic [22]. In a similar way, systems engineering can be applied to organize and guide a survey research project.

Systems engineering can be used to integrate existing survey research knowledge. Systems engineering can bring together various silos of expertise that are well understood and documented in the existing survey research methods literature (e.g., sampling, question writing, survey data analysis) in a way that has potential to increase the effectiveness of survey research. In addition to a general perspective, systems engineering offers specific processes, methods and tools that can be further leveraged to enhance survey research.

Systems engineering processes support the engineering of complex system elements in manmade systems. As a result, many organizations have defined and specified processes for engineering systems [23-26]. Those who engineer systems can follow these processes to organize and guide their efforts to ensure that a system is delivered to a customer that satisfies the customer's requirements. A few systems engineering processes are common to multiple systems engineering standards and are highly applicable to survey research. These processes include technical processes and management processes. This paper will examine stakeholder requirements analysis, architecture design, implementation, validation, verification, project planning, risk and opportunity management and information management in the context of survey research. For each of these processes, there are various methods and tools that are applied to satisfy the process objectives.

3.1. Stakeholders Requirements Analysis

A stakeholder is anyone who is involved in or affected by a course of action [27]. Stakeholder requirements analysis involves understanding stakeholder needs so that the system can provide necessary services to acquirers and other stakeholders [25]. A survey project has stakeholders. This set of stakeholders and their needs should be considered from the inception of a survey project. Examples include the acquirer of the study results, others who will eventually use the findings from the research or be affected by the application of the research, the base of potential qualified survey respondents, the institutional review board (IRB) and individuals or organizations that assist researchers in recruiting participants. Each of these stakeholders and their requirements are discussed below.

The Acquirer - The acquirer of survey data is the person who needs an answer to a research question. This may be someone who sponsors the research or it may be the researcher. A survey project satisfies the acquirer if it provides data that is sufficient to address the research questions. In the case study, the acquirers are the researchers searching for an optimal use of systems engineering on proposals.

Others Interested in and/or Impacted by the Results - Decision makers may eventually use the results from a survey to set policy or to guide investment decisions. Other researchers also may use the results to guide their research. If the findings of the survey research are invalid or are misapplied, negative consequences may ensue. Because of this, researchers should exercise great care in how they present the results of the survey analysis. Study limitations need to be explicitly stated, and threats to validity need to be clearly explained.

Respondents - Characteristics of the base of qualified respondents also impact a survey research project. The level of motivation, interests and skills of the respondent base can be major factors that influence decision making in a survey project. For example, the level of motivation of the set of potential, qualified respondents may impose

constraints on the length of a survey. People interested in a specific professional topic may have more tolerance for a lengthy questionnaire than members of the general public might when evaluating a consumer product or service.

For any given survey, respondents may be familiar with certain terminology and concepts. Leveraging that familiarity should be a consideration in the survey design and question formulation. In the case of a survey that is targeted at a specific community, members of that community may generally be familiar with certain concepts. Capitalizing on that familiarity may allow a large amount of information to be elicited efficiently. Less explanatory information may be necessary, and a great deal of information may be obtained through a few questions targeted at concepts familiar to the respondent base.

The base of qualified respondents may also impose constraints. For example, organizations who hire certain potential respondents may not allow the release of the certain data items to be collected by a survey because of potential risks to the organization. Also, if the majority of potential respondents are within a particular segment, such as large corporations, there may be restrictions on the use of information technology that can impact online surveys. Many of the respondents for the case study survey work for large defense contractors who limit the set of websites employees may access without obtaining prior approval. An online survey hosted on a domain that has not been preapproved may be inaccessible to people within such internet firewalls. This can impact the response rate and validity of the survey research.

Institutional Review Board - Researchers employing surveys may require the approval of an IRB per organizational policy. IRBs generally need to review the final product that will be shown to participants before they can approve the research. Generally, IRBs ensure that participants in experiments are ethically treated and not subjected to any undue risks. University IRB approval was required for the case study.

Organizations Supporting Respondent Recruitment - A final stakeholder for a survey is any individual or organization that helps the researchers recruit participants. Often individual researchers using survey methods do not have access to large enough groups of potential qualified respondents to gather a sufficiently large sample of data. When this is the case, it may be necessary to request assistance from key individuals or organizations to reach more potential respondents. In the case study, the membership of key professional societies was targeted. The set of professional societies was selected because their membership includes the types of professionals who possess the specialized knowledge necessary to answer the survey questions.

For individuals or organizations to be amenable to provide assistance recruiting respondents, they generally need to benefit in some way from the study. For professional societies, a research focus aimed at challenges within the professional community may be sufficient. The survey researcher should clearly articulate the potential benefits when requesting help from professional societies. In the case study, the researchers carefully selected a name and crafted a description of the research so that it would be clear why assisting such research would be beneficial. As a result, several professional organizations sponsored a link to the case study survey and in some cases sent emails requesting their members to participate.

Organizations that may help reach participants generally have policies that must be followed. Some organizations may explicitly publish these policies while others may communicate these policies once a researcher contacts them. In either case, it is up to the researcher to become familiar with these policies and understand how these policies affect the survey research. For example, if an organization will not support a survey if the survey requests information to identify respondents, then it is useful to know that early in the research process. If the help of such organizations is to be sought, survey researchers may potentially have to rethink certain details such as how to distribute incentives to respondents and also how to authenticate responses.

Literature analysis and prototyping were the primary methods used to elicit requirements from various stakeholders for the case study. Many of the requirements for the survey research were determined by reviewing the existing body of survey research method literature as well as information from related and relevant surveys [2,28]. Other requirements were discovered from expert feedback from various iterations of prototypes of the survey. While no specialized tools were used in the requirements analysis, rigorous manual traceability was done between the factors and the questions in the research.

3.2. Architecture Design

Architecture is “a unifying or coherent form or structure” [27]. Architecture design is the process of designing a system so that there is a logical fusion of elements working together. A system with a sound and logical architecture

has an advantage in achieving its objectives because the framework exists to allow the system elements to function harmoniously. Likewise, a survey project with a sound and logical architecture has an advantage in achieving its research objectives.

Survey research project architecture includes considerations such as how the group of potential respondents will be approached to participate and how those members will provide the necessary data. For the case study, it was determined that the ideal way to approach members of the professional societies to participate was to both send an email and make the survey link accessible on the websites of the organizations who helped recruit participants. The content of this email and the text associated with the survey links are critical elements of the survey research architecture. If this material does not compel a potential respondent to click the link and begin viewing the survey, then it is immaterial how impressive the survey is because the potential respondent will never see the survey. This first contact material was carefully crafted to provide a succinct yet accurate description of the survey research, its importance and the qualifications required to participate.

Every survey form has an architectural design, regardless of whether that design is intentional or not. A good architecture design can improve the organization and flow of the survey. As the respondents are stakeholders in a survey project, a well-organized survey form that flows smoothly may yield a higher response rate than one that is more difficult for respondents. It is important to group related questions together and provide explanatory information in a way that is accessible when respondents are answering each question. In the case study, a set of core terms are used throughout the survey, and the integrity of the research depends on respondents having common interpretations of those core terms. Because of this, the core terms are defined near the beginning of the survey and referenced each time that they are used in the survey.

The methods used for developing the architecture of the questionnaire for the case study include a careful review of an analysis previously conducted to examine the relationships between various factors in a systems engineering strategy framework [29]. The architecture layout of the survey is based upon relationships within and between relevant classes and attributes in the systems engineering strategy framework. Because of this, an object-oriented modeling method was used.

3.3. Implementation

Implementation produces a specified system element [25]. Some of the details of implementing a survey depend on what type of survey is being administered. For mail surveys, a great deal of the implementation effort may pertain to researching addresses, coordinating mail outs, and encoding responses. For online surveys, the effort is predominately implementing the electronic survey and ensuring that the survey functions properly on an appropriate variety of operating systems and internet browsers.

For the case study survey, a trade study was conducted for the types of software tools to use to develop and host the survey. The case study survey is rather complex from a formatting perspective, involving question groups separated with significant explanatory information, many tables and figures, and data that is best entered in a tabular/matrix form. Because of these challenges, the authors initially ruled out off-the-shelf (OTS) survey tools and elected to implement the survey by designing custom web pages. Once the decision was made to implement the survey via custom designed web pages, more detailed implementation decisions had to be made related to who would host the survey. University information technology offices provide faculty and students with a core set of software and hardware resources. In the case study survey, the decision was made to consider host services external to the university to host the survey because the authors wished to leverage software that was not in the core set offered by the university. A formal trade study was conducted using several web hosting services that ranked highly in an independent consumer-focused study [30]. The criteria in the trade study were cost, security, support of enabling technology (e.g., software) and customer service.

Despite the methodical process, the custom web page version of the survey was largely unsuccessful at eliciting responses because an important requirement had been overlooked. Many of the respondents work for organizations who implement very stringent controls on the use of the internet, and in some cases block sites that have not explicitly been pre-approved, such as the commercial service hosting the case study survey. As a result, the survey had to be re-coded in a commercial OTS tool that an analysis revealed to be accessible from within the firewalls of several organizations that employ potential respondents.

For internet based survey implementation, the methods used for coding a survey are generally a subset of the

methods software developers use (e.g. prototyping). The details of how to implement a survey vary depending on the exact tool used and related environment or language required to code the survey. Some OTS tools provide a development environment where no specific coding is necessary to implement basic functionality. In such tools, custom code can sometimes be used to customize graphics or attributes of the survey beyond what is offered as standard. Other tools require more custom coding.

3.4. Validation

Validation provides evidence that the services provided by a system, when in use, comply with stakeholders' requirements [25]. A survey can be considered valid if it elicits information that is adequate to correctly answer the research questions posed by the sponsor or researcher. Validating a survey is critical to the integrity of a research project because valid surveys are necessary to elicit valid data, and valid data is necessary to lead to valid findings in a study. For the case study survey, several panel discussions and informal communications were used as methods to validate the survey. The dissertation committee reviewed the analytical model that related factors to the research question and also reviewed the survey questions. The set of factors was also reviewed by members from a university industry advisory board to ensure that the set covered the logical candidates to predict proposal success. As a result of this review, two additional questions were added to the authors' original list. Subject matter experts were used to validate the terminology and clarity of the survey questions.

The survey instrument was then validated by field testers and expert reviewers. Field testers input real data into the survey for all required fields and provided feedback about any issues that they encountered as a result of populating the survey. Expert reviewers are people with the knowledge base representative of the core survey respondent demographic, but who are unable to input the required data. For the case study survey, five people were approached to field test. Three actually input data into the survey form and all five provided feedback. Of the three who input data, one entry was sufficiently complete to be considered a field test. In retrospect, it was helpful to have approached multiple individuals to field test because only one in five was able to provide sufficiently complete inputs to truly serve as a field tester.

3.5. Verification

Verification confirms that the design requirements are satisfied by the system [25]. There are multiple types of verification activities that should be done as part of survey research throughout the survey lifecycle. These activities include verifying the survey questions are correct and verifying that the survey instrument is correct. This verification is done by both the survey researchers as well as a number of other individuals who are consulted throughout the survey lifecycle. Adequate time and resources must be planned to accommodate verification.

Once survey questions are written, it is necessary to verify the survey questions and content. After questions are formulated, verify that each data item required to support the larger study is effectively elicited by at least one question on the survey. After that, verify that each question is well-constructed by evaluating it against the best practices from the survey research literature guidelines for effective question writing [10,12,16].

Another type of verification that is especially applicable to internet-based surveys is verification of the survey implementation. This includes the survey forms, the server hosting the survey and whatever software is used by respondents to access the survey and record responses. The primary method used for verifying the case study survey was that a verification plan was documented, refined, reviewed and implemented. As such, carefully planning and executing a verification plan increases the likelihood of the survey working as designed and decreases the risk of a technical glitch compromising opportunities to collect data. The authors constructed a verification plan and set of verification procedures for the survey. The procedures were executed in a number of computer environments, where different operating systems and different browsers were used. Different anomalies were found and fixed in different environments.

After the verification procedures were executed by the authors, other testers were engaged. These testers in some cases concurrently validated and verified the survey. Generally, testers provided both feedback that allowed errors to be corrected and feedback that allowed questions, directions and explanatory information to be clarified. The first round of testers included peers, committee members and testers with specialized, relevant skills. The specialized testers included one English major who taught high school grammar for decades and has a firm grasp on the rules of

English. Another specialized tester writes and maintains database software. This tester has expertise in how data recording software works and various inputs that are likely to create challenges for such software. The intent of these tests was primarily to find mistakes and technical issues. However, some feedback from these testers provided an opportunity to clarify questions, directions and explanatory information and hence could be considered validation. The second round of testers included the field testers and expert reviewers previously identified to provide a final validation of the survey. In the case study, none of the field testers or expert reviewers reported finding errors. Nonetheless, by performing such field testing, the survey instrument was reviewed by several additional people, which provided additional confidence that the survey worked as expected and would collect the needed data.

The tools used to support verification for the case study were the survey-specific software, the internet, various browsers and operating environments that resemble what the base of respondents is likely to use to access the survey and standard office software (e.g., word processing software for documenting verification plan, spreadsheet software for analyzing sample results).

3.6. Project Planning

Project planning supports devising effective and workable plans for executing a project. Project planning identifies project tasks and deliverables and completion criteria, establishes schedules for conducting the project tasks and identifies the required resources to accomplish project tasks [25]. Survey projects involve a number of interdependent tasks. Some tasks take time for the researcher to accomplish and some tasks impose delays. Careful project planning is necessary to coordinate the tasks as well as to budget time and resources. Tasks need to be sequenced and prioritized. However, there is a limit to how precisely one can realistically plan when conducting survey research.

In the case study survey, project planning was done throughout the survey lifecycle. This planning determined the sequence and timing of various activities on the survey project. The method used to create this schedule was to define tasks, milestones and relationships between those tasks. The tool used was simply a word processing tool. It is conceivable that a formal project management or scheduling tool could be used to describe tasks and the relationships between the tasks. A cost/benefit analysis may need to be done to determine whether the rigor of formal scheduling justifies the time and cost of specialized software.

Despite this careful planning, the original projected date for which the survey was to "go live" proved optimistic. This is because the researchers encountered unanticipated challenges and opportunities throughout the survey lifecycle. One challenge was arranging for an alternative service to host the survey once it was determined that the desired software was not included in the university core set. One unanticipated opportunity was an invitation to present the set of factors assessed by the survey to a university industry advisory board composed of leaders from industry, many of who are experts in using systems engineering in the proposal process. The feedback from the advisory board provided highly beneficial input, and resulted in improvements to the survey. However, because of the timing, the impact was that the original schedule was extended.

3.7. Risk and Opportunity Management

Risk and opportunity management is conducted to reduce the likelihood or the impacts of negative uncertain events or improve the ability to capitalize upon positive uncertain events. Risk and opportunity management identifies, assesses, treats and monitors risks during a system's lifecycle phases, responding to each risk with an appropriate course of action [25].

As with most projects, identifying and managing risks for survey projects is necessary. For survey research, one major type of risk is potential threats to validity. Risk management provides a framework to govern the identification, assessment, monitoring and the mitigation of potential threats to validity throughout the survey lifecycle. Even when a threat to validity must be accepted, carefully and methodically addressing threats to validity throughout the survey lifecycle can ensure that the threats are accurately and clearly documented when the results are presented.

Threats to validity can be internal or external. Findings from a study have internal validity if effects observed in the dependent variable are actually caused by the independent variable and not by other factors [31]. One potential

threat to being able to draw meaningful inferences for the case study survey was insufficient sample size. To mitigate against insufficient sample size for the case study, several professional organizations and chapters within those organizations were contacted in an attempt to reach as large of a sample population as possible.

External validity refers to whether the casual relationships from the study can be generalized beyond the study conditions [31]. In other words, for this research to be externally valid, the findings would have to apply in general for proposal efforts where complex systems are being engineered. For the case study survey, it is unknown to what degree people who are members of the professional organizations that were approached to support the study represent the population of people with knowledge of how systems engineering is applied on proposal efforts. This poses a potential external threat to validity and a limitation. This issue will be carefully and accurately explained when presenting the survey results.

For the case study, brainstorming and discussions with subject matter experts were the primary methods used to identify potential threats to validity. These potential threats are revisited when various decisions are made throughout the survey lifecycle. The tools used are spreadsheet and word processing software. It is conceivable that specialized risk management tools could be used to manage potential threats to validity. It may be advisable to perform a cost/benefit analysis before investments in tools or training are made related to such specialized software.

3.8. Information Management

The purpose of the information management process is to provide relevant and timely information to the designated parties while protecting confidential or proprietary information [25]. Effectively managing information is critical to a successful survey research project. Information management is a key enabler to successful relationship management with each of the survey stakeholders. For example, the acquirer should be informed regularly about the status of the survey project and then be informed about the results and analysis of results. Respondents must be informed about how, when and why to respond. In many cases, the IRB must be informed about all materials that are to be presented to respondents. Finally, individuals or organizations that support recruiting participants must be informed about the benefits of supporting the research, how to contact respondents and when to contact respondents. In many cases, such organizations may also wish to be informed about the survey results and findings.

For surveys, the most important type of information to be managed is the data. Researchers must be able to access that data to answer their research questions. Various stakeholders (e.g., sponsors, IRB) may require that data be kept for a particular length of time. Keeping data allows a study to be audited or replicated if necessary.

In most surveys, individual responses are confidential. Therefore, data collected by a survey should not be accessible to unauthorized parties. Depending upon the nature of the data collected from a survey, there may be laws or regulations that require certain processes and procedures be followed or requirements be met to protect respondents' confidentiality. For internet-based surveys such as the case study, it is essential to verify that unauthorized individuals are not allowed to view the data collected from the survey.

As the analysis of the survey data is ongoing for the case study, no specifics can be shared about the exact methods used to manage the data. However, all decisions are made in the context of maximizing the likelihood that the data will remain accessible to the people who are supposed to have access while minimizing the likelihood that the data will be accessible to those who are not supposed to have access. The tools that are generally used are access control software and locks and other constraints that help secure physical premises.

4. Summary of Recommendations and Conclusions

The authors' experiences designing, implementing and launching an online survey to support dissertation research are analyzed in this paper in the context of systems engineering processes, methods and tools. The processes analyzed included stakeholder requirements analysis, architecture design, implementation, validation, verification, project planning, risk and opportunity management, and information management. As a result of the analysis, a number of specific recommendations are provided throughout the paper.

Table 1 discusses the current state of survey research and how systems engineering may be applied to improve survey research.

Table 1. Key contributions of systems engineering in survey research

Current state of survey research	Systems engineering provides …
Each activity addressed separately	A framework to integrate activities to achieve research objectives
Limited consideration of stakeholders	Processes, methods and tools to address requirements from all stakeholders
General best practices primary guide quality control	Established processes, methods and tools for verifying and validating the survey
Threats to validity largely considered after the fact	Risk and opportunity management framework to manage and mitigate potential threats to validity throughout survey lifecycle

Researchers who use survey methods should consider the guidance in this paper as well as the recommendations offered by other survey methods literature. For systems engineering researchers who need to collect data via surveys, this paper presents a possible point of entry into the survey research methods literature because it invokes a familiar analogy: engineering a complex system. Examining a survey research project through a systems approach as a means to satisfy stakeholder needs provides clarity of purpose and a perspective that helps guide decision making throughout the survey lifecycle. This will help ensure a more successful result.

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