9-9-2019

Integrating narratives into decision making for complex systems engineering design issues

Cameron A. MacKenzie
Iowa State University, camacken@iastate.edu

Kris Bryden
Iowa State University, kabryden@iastate.edu

Anna A. Prisacari
Iowa State University

Integrating narratives into decision making for complex systems engineering design issues

Abstract
Engineering decision making and design requires collaboration between groups from different disciplines, each with different tools, vocabulary, and concerns. Traditional engineering decision-making tools are generally based on understanding the decision makers' values, modeling uncertainty with probability, and selecting the alternative that maximizes utility. This rational approach to decision making may not be well understood or used by many stakeholders involved in the engineering design process. Constructing narratives, a basic means of human communication, may aid in engineering communication and comprehension and help with decision making. Narratives represent events by means of a story and usually include characters or agents who cause events and to whom events happen. This paper recommends three methods for how the use of narrative can be applied to the area of engineering decision making. These methods include connecting the decision maker to the analysis, creating narrative simulations for training decision makers, and fostering consensus in problems with multiple stakeholders. An illustrative example of designing a better cookstove for the developing world demonstrates the role that understanding narratives of various stakeholders can play for accomplishing complex systems engineering.

Keywords
complex systems, decision science, narrative theory

Disciplines
Other Arts and Humanities | Other Communication | Other Operations Research, Systems Engineering and Industrial Engineering | Systems Engineering

Comments
This is the peer-reviewed version of the following article: MacKenzie, Cameron A., Kristy A. Bryden, and Anna A. Prisacari. "Integrating narratives into decision making for complex systems engineering design issues." *Systems Engineering* (2019), which has been published in final form at 10.1002/sys.21507. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions

Integrating Narratives into Decision Making for Complex Systems Engineering Design Issues

Cameron A. MacKenzie, Kris Bryden, Anna Prisacari

Abstract

Engineering decision making and design requires collaboration between groups from different disciplines, each with different tools, vocabulary, and concerns. Traditional engineering decision-making tools are generally based on understanding the decision makers' values, modeling uncertainty with probability, and selecting the alternative that maximizes utility. This rational approach to decision making may not be well understood or used by many stakeholders involved in the engineering design process. Constructing narratives, a basic means of human communication, may aid in engineering communication and comprehension and help with decision making. Narratives represent events by means of a story and usually include characters or agents who cause events and to whom events happen. This paper recommends three methods for how the use of narrative can be applied to the area of engineering decision making. These methods include connecting the decision maker to the analysis, creating narrative simulations for training decision makers, and fostering consensus in problems with multiple stakeholders. An illustrative example of designing a better cookstove for the developing world demonstrates the role that understanding narratives of various stakeholders can play for accomplishing complex systems engineering.

Keywords—complex systems, decision science, narrative theory

1. Introduction

Engineering design usually attempts to follow a predefined process in which requirements are defined. A team of designers seeks to build models or develop designs that could satisfy those requirements.[1] A mathematical model can help determine whether a design is feasible and whether the design meets the requirements. The preferred design might be the one that minimizes cost subject to meeting all of the requirements. Other design processes, such as value driven design, may not consider every requirement as a constraint that must be satisfied but view a requirement as an objective to be minimized or maximized (e.g., minimize weight rather than requiring that weight must be less than a predetermined value). If the objectives conflict with one another, multi-criteria decision-making methods can be implemented to identify the best alternative. If uncertainty exists in the problem, the best design is one that maximizes the expected value for a risk-neutral decision maker or expected utility for a risk-averse decision maker.[2,3] The alternative is then implemented.

That is how engineering design is supposed to work, at least in theory. In practice, engineering design is a messy process, even chaotic, as are most decision-making processes within organizations.[4] People have hidden or not-so-hidden biases that influence their preferences and how they think about uncertainty.[5,6] Engineers may have different models for predicting how a system will perform, and each model requires assumptions, which may not always be valid. Complex decision making requires making trade-offs among multiple objectives, and designers may struggle determining how to make those trade-offs. Many complex decisions also involve multiple stakeholders and decision makers. These decision makers may not have the same objectives and preferences, or they may not agree about trade-offs. In these cases, an engineering design solution requires arriving at a resolution among these different points of view or having a single individual with the authority to make a decision even if all of the stakeholders cannot come to an agreement.

A general overview of this process is depicted in Figure 1. The process begins with identifying the stakeholders who participate in the decision-making process and their goals, needs, biases, objectives, and preferences. To achieve a common resolution, this paper proposes three methods that can enhance decision making in systems engineering by integrating narratives into each method. These methods can more accurately reflect the reality of the engineering design process.[4] Creating a narrative is the act of constructing a story with agents and events that happen to those agents or are initiated by the agents.[7,8] The sequence of events and the purpose and meaning of the narrative help create the narrative structure.[8,9]

People have long been attracted to good narratives, and narrative theory explains how stories help us make sense of the world around us and in the past, and how people make sense of these stories.[10] We are attracted to and moved by emotional or exciting narratives that resonate with our own feelings and desires. Therefore, it is not surprising that people often tend to think in terms of narrative (e.g., how they have experienced or could experience an event). Because narrative represents a fundamental aspect of the human psychological experience,[11] incorporating narratives may facilitate engineering design and the decision-making process. Narrative theory has been explored in the humanities and the act of constructing narratives has been discussed as a decision-making process in some fields, such as medicine,[12] policy,[13] project management,[14] and the sciences; for example, Warfield [15] describes Generic Design Science, a major portion of which involves structured methods for eliciting information from stakeholders similar to communicating via narratives. Moreover, some have explored how engineers incorporate telling stories on an informal, ad-hoc basis in the engineering design process [16] and the value of telling stories in the design process.[17-19] However, a formal process of how constructing narratives should be integrated into the design of complex systems for engineering design has not been presented.

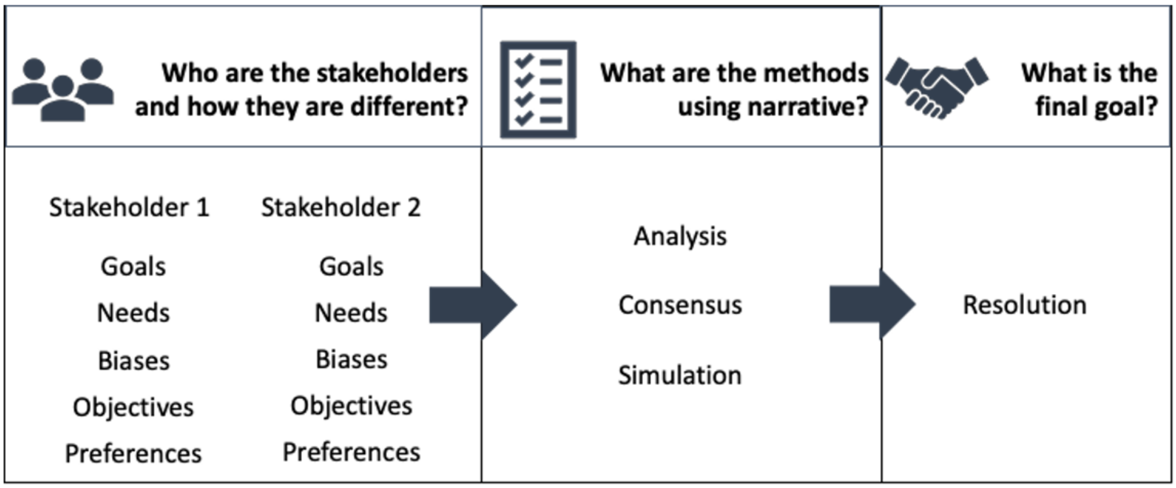

Figure 1. Narrative and the engineering design process

The unique element of this paper is the explicit attention to and focus on how narrative can be integrated into the engineering design and decision-making process. Although the questions in the case studies described by Warfield [15] are similar to the types of questions suggested in this paper, Warfield's objective is to create and present an overall structure for the science of complex systems design. By focusing specifically on the use of narrative to enhance communication between a decision maker and an analyst or among multiple stakeholders, the process described herein introduces new methodologies for analysis and a new perspective about how the formation of narrative can enhance systems engineering and analysis.

Because systems engineering problems typically include human and organizational behavior, qualitative methods can help elucidate challenges in systems engineering and offer potential solutions.[20] Checkland [21] argues that "hard" quantitative systems thinking that focuses on solving problems based on an organization's goals is a subset of "soft" qualitative systems thinking, which is more oriented to learning. Traditional engineering methods that seek to solve a problem by clearly defining goals and objectives may not work with messy, ill-defined problems. Rather, soft systems methodology seeks to encourage different perspectives about an issue so that stakeholders can compare those perspectives and models. By learning about an issue rather than optimizing to find a solution, soft systems methodology provides a roadmap to find accommodations to issues.[21]

The uses of narrative theory presented in this paper echoes the soft systems methodology, as narrative theory will not directly produce solutions to systems engineering design. Narrative can provide avenues for people to engage within complex engineering issues. This paper recommends three methods for how the use of narrative can be applied to the area of engineering decision making. The methods are summarized in Table I. First, a process that explicitly integrates a decision maker's narrative into the analytical process can facilitate understanding by the decision maker. Second, simulations are increasingly being used as part of the engineering design process, and using narrative within a simulation can provide an effective means of training people to make decisions in complex situations. Third, many complex decisions involve multiple stakeholders with different values and opinions. The use of narrative can help stakeholders understand each other's point of view and promote consensus among those stakeholders.

Table I Summary of three methods for including narratives for engineering decision making

	1. Analytical process	**2. Simulation training**	**3. Multiple stakeholders**
Who is affected?	Decision maker(s) and the analyst(s)	Decision maker(s)	Group members and stakeholders
Role of narrative	Understand the analysis	Bring the user into a simulated environment	Understand different points of view and achieve consensus

Benefits	See the connection between different pieces of information	User engagement and successful training	Connect decision makers
Challenges	Decision maker's narrative may conflict with the analysis	Integrate narrative into the simulated environment in an engaging manner	Different, multiple narratives may be possible
Future research	How to construct analysis so it aligns or makes use of narrative	How to use game technology to enable interactive narrative for training purposes	How to achieve convergence between competing narratives

The rest of the paper is structured as follows. Section 2 develops a definition of narrative that is beneficial for using as a tool for engineering decision making and reviews the literature on engineering design. Section 3 introduces and discusses in detail the three methods for integrating narratives into engineering decision making. Section 4 applies the concept of constructing a shared narrative in the process of designing a cookstove for the developing world. Concluding remarks with directions for future research appear in Section 5.

2. Literature Review

2.1 Background on Narrative

Developing criteria for a narrative is a difficult task. Various narratologists (scholars who study narratives and narrative structure) have developed various models from differing perspectives.[22] Indeed narrative has been described as a "fuzzy set defined at the center by a solid core of properties, but accepting various degrees of membership."[23(p345)] Most of these narrative models elaborate on several basic elements encapsulated in a definition proposed by Abbott:

> **“Narrative** is the representation of events, consisting of *story* and *narrative discourse*”[11(p19)]

“Story,” according to Abbott,[11(p19)] consists of “the events and the entities” (characters if they have human qualities), and the narrative discourse is “those events as represented.” That is, the narrative discourse is all about how the story is constructed and the medium used for its presentation (e.g., novel, film, informal conversation) as well as why the particular events and entities for the story are chosen. For a narrative to have value—that is, for it to be interesting and fulfilling—a narrative should include elements that provide a sense of causation, normalization, and closure.[11]

For the purposes of using narrative for decision making in engineering design, we propose using the basic definition of narrative proposed by Abbott outlined above as a starting place and then adding elements that are valuable to the decision-making process. As a starting place the story must include at least one event [9] and one entity. For this paper, we will use the term *character* if referring to an entity with human characteristics or *agent* if the entity is nonhuman—the weather, for example. Additionally, the story must be presented in some manner. For constructing narratives that can be used as a valuable tool in an engineering decision-making process we propose adding the following five aspects:

1. Goal.[9] Providing a goal imparts a sense of purpose and fulfillment and closure when the goal is reached.
2. Setting. To add a sense of normality and provide an orientation for a narrative, it should provide a sense of when and where the action occurred (or will occur) as well as who performed what actions.[9(p69)]

3. Conflict. Defined by Prince as "the struggle" in which the entities in a narrative are engaged,[9(p15)] conflict is an important and common aspect of many narratives, and conflict demands resolution, which keeps the ones receiving the narrative more invested in it. Conflict can be thought of as the challenges and obstacles one faces in the design process.
4. Actions taken to overcome challenges and to answer questions. Narratives generally include actions that move the story forward [9(p3)]; however, for the purposes of using narrative as a tool for facilitating engineering decision making, these actions should be targeted toward overcoming design challenges and to answer questions that are brought up in the course of the narrative.
5. Result or resolution. Answering the questions brought up in a narrative will give it a sense of closure and completeness. These questions and the ensuing answers are "accomplished predominantly through the causal networks in the story."[24(p15)]

When narratives are included in the engineering decision-making process, they sometimes conflict with each other. These competing narratives may at first glance seem detrimental to the engineering decision-making process. However, if managed appropriately they can be helpful. Todt [25] explains that including and managing "social" controversy is advantageous to the engineering design process. A study by Amason [26(p127-129)] shows that conflict can improve the quality of a decision if it is a "cognitive" conflict ("task oriented and focused on judgmental differences about how best to achieve common objectives") or hinder the decision-making process if it is "affective" conflict ("emotional and focused on personal incompatibilities or disputes"). In the field of project management, Boddy and Paton [14(p266)] note that competing narratives arise from projects that involve uncertainty, integration, and urgency.

They contend that competing narratives matter a lot when they arise from “deeply held, but unacknowledged,” differences of perspectives within the organization. These differing perspectives result from various subcultures, structural divisions, and differing abilities to influence events. Boddy and Paton discuss two methods for managing competing narratives to benefit the project. These methods include performing a stakeholder analysis to understand the interests of those involved in the project and creating a structure that enables those involved to work together, discuss issues, and understand constraints as well as other benefits.

In another type of narrative involving conflict, rather than *telling* competing narratives, the characters in the narrative *undergo* some kind of conflict themselves that may result in a satisfactory resolution or not. This conflict is generally one that is common to human experience and serves to energize the course of the narrative. It serves as a catalyst to engage the reader's concern for the characters. Narratives may not end with a successful negotiation of the conflicts within them, but they do draw us in and help us become aware of how conflicts are played out, thus providing a mechanism for "passionate thinking" that engages the emotions.[11(p199)]

Narrative theory can help explain how and why public policy decisions were made.[27,28] Narratives have been suggested as a means to advocate for a specific policy outcome, and key variables (e.g., the importance of meaningful characters, the existing public opinion, and connectedness within the narrative) may help advocacy organizations use narratives in order to be more persuasive.[29,30] Narrative communication may be used to promote public health objectives and support individual decision making.[31] Studies in health communication focus on whether or not a narrative changes people’s attitudes and intentions about health risks and behaviors.[31,32] Murphy et al.[33] find that a fictional narrative about cervical cancer does a better job at increasing health-related knowledge and behavior compared with presenting identical information in a non-narrative format. These findings seem to indicate that narratives can be a powerful communication tool, and this paper applies those ideas to the field of systems engineering design.

Recently interactive narrative has been proposed as an alternative to the classical approach to narrative where a narrative is told by an author to an audience. In an interactive narrative, the story emerges over time within a given setting. To enable interactive narratives within games, Mateas [34(p148)] proposes a new model for interactive storytelling where players would have greater opportunities for interaction and to make their own choices; that is, according to Mateas, "provide the player with a strong sense of agency." Mateas also proposes and provides an example of a game using a technical approach that facilitates this greater sense of interaction.

Another approach to interactive narrative draws on improvisational drama and role-playing games to dynamically generate stories in a virtual 3D environment. Improvisational drama and role-playing games provide a way to more equally divide up the decision-making process and allow for more participation in the process.[35]

2.2 Engineering Design

Engineering design is essentially a decision-making process.[36] Therefore, the theories and practices developed to help make good decisions can be applied to design.[37] Value-focused thinking encourages a decision maker to first think about objectives that he or she wants to achieve and then identify specific attributes that help to measure the decision maker's achievement on each of those objectives.[38-43] Value-driven design identifies attributes within a system and models the value a firm or a designer can achieve from each attribute. It usually uses multi-attribute value theory in order to combine the attributes into a single number.[44-46] Multi-criteria decision analysis can allow a designer to explore the tradespace and determine trade-offs among the different attributes.[47] Providing designers with multiple alternatives each of which is Pareto optimal may also help them make better decisions and consider these trade-offs.[48] As will be discussed, many of these ideas about values in design align with the use of narratives.

Dialogic Design Science [49] or previously referred as the Generic Science of Design [15,50] brings together a set of beliefs in order to support the design and development of new products. As part of the Generic Science of Design, Interactive Management [51] describes the foundational elements to manage the complexity of design. It employs many different techniques developed to benefit engineering and system design, including the Nominal Group Technique and Interpretive Structural Modeling. As an outgrowth of Dialogic Design Science, the Structured Dialogic Design methodology encourages dialogue among stakeholders—which is similar to communicating via narratives as suggested in this paper—and has been applied to issues involving capabilities-based planning in the military,[52] citizen participation in democracies,[53] and the safe use of pharmaceuticals.[54,55] The CogniScope is the name given to a bundle of products and software that implements Structured Dialogic Design and encourages collaboration and interaction among stakeholders within systems design.[55]

The Unified Program Planning methodology [56] provides a visual tool used to link and display relationships among planning techniques in the design process. These visual tools can help elucidate and simplify a very complex design process. Concurrent engineering is a team-based approach to design.[57] Quality Functional Deployment is a technique to incorporate consumer preferences into the design of new products.[58] Tools to enhance design or decision making in design should focus on including people within the design and on improving communication among the design team members and between the designers and the customers.[57] These tools foster communication among the design team members and help to understand preferences. These communication tools provide ways to discuss narratives or stories within the design phase. For a recent review, see Laouris and Michaelides.[49]

The engineering design community has benefited from a vast amount of research into modeling the preferences of the customer in order to inform design decisions.[59,60] Engineering design is increasingly coordinating with marketing departments to understand how best the design will satisfy consumer preferences.[61] Consumers may have preferences that are not well expressed or not well discernible by firms.[62,63] Integrating the preferences of the design team should also be used in addition to understanding consumer preferences.[64] Public policy questions may require eliciting preferences of many different stakeholders.[65,66]

Fuzzy set theory has been used to generate imprecise preferences for engineering decisions and public policy modeling.[67-69] Fuzzy preferences can also be used to assign weights for multi-attribute decision problems.[69] Assessing preferences of experts in group decision making can be used with fuzzy preferences.[70] Representing this imprecision due to uncertainty about consumer preferences with imprecise probabilities may represent a useful approach in engineering design.[71]

The literature shows that a decision maker’s preferences can be influenced by the frame, the decision maker’s own biases, and the way the decision is presented or understood.[72,73] The construction of a set of choices also influences a consumer’s decision-making and buying choices.[74] A designer’s experience or possibly his or her lack of experience can influence the designer’s personal preferences in selecting design alternatives.[75] Computer tools can assist with the design process. It may be better to start with low fidelity design models that gradually increase in complexity.[76]

The literature connecting narrative to systems engineering and engineering design focuses primarily on communication between the designer and the user. Gruen et al.[17] study how stories can be used to capture and describe user experiences for software within the IBM corporation. Madni [18,19] proposes the use of storytelling to explain model-based systems engineering to laymen within a virtual environment. Lloyd [16] argues that engineering design is more of a social than a technical process, and he employs ethnographic research methods—which include analyzing storytelling mechanisms—to generate insight into the engineering design process.

3. Methods for Integrating Narrative

Systems engineering design usually refers to the process by which the needs of the customer or stakeholder are translated into specifications or requirements. The design seeks to meet those specifications through the integration of components into a system, and the system is tested or validated against those specifications.[77] Design includes identification of user needs and requirements, preliminary concepts, item configuration and design, system integration, validation, testing, and refinement. The complexity of the system design process may require sophisticated data modeling tools, such as entity-relationship diagrams [78] and the Integrated Definition (IDEFØ) Function Modeling method.[79] Elegant system design seeks to stimulate the creative process by engaging designers and users in the design process.[80]

Decision makers and stakeholders (e.g., government entities or company managers) who are involved with the engineering design may not be familiar with tools and methods typically used in systems engineering design. The decision frame identifies the goal of the decision problem, what is included in the analysis, and what will be left out of the analysis.[81] Getting the analyst(s), decision maker(s), and other stakeholders to agree on a frame for a design issue may pose significant challenges.[82]

Formally and explicitly integrating narrative into the engineering design and decision-making process can further communication between systems engineers and non-engineer stakeholders. Narrative enables the decision frame to be communicated in a more natural manner among the various stakeholders that may be involved in an engineering design. We identify three basic methods for how narrative can be integrated into the engineering decision-making process: (i) connecting decision makers with the analysis, (ii) building a narrative within a simulation, and (iii) promoting consensus among multiple stakeholders.

3.1. Connect decision makers with analysis

Decision makers may feel disconnected from systems analysis because the analysis can seem dry and uninspiring. The analyst may be geographically removed from the decision maker and might conduct the analysis without input from the decision maker. Consequently, a decision maker may not understand or trust the analysis and proceed to make a decision without considering the analysis.[83,84]

Creating a shared narrative between the analyst and decision maker can help the decision maker understand and determine the frame for analysis because the analysis will better reflect the design goals and objectives. This shared narrative provides a means of communication for the analyst to understand the decision maker’s objectives, goals, and constraints. For example, Wieck [85] argues that people within organizations that value telling stories are more likely to know more about the complex system with which they are working and be more aware of errors that might occur. Because a narrative's value depends on how well it serves the interests of both the narrator and receiver when the narrative is told and received,[86] the narrative between the analyst and the decision maker should reflect the concerns of both participants. The narrative will provide more background and context for the analysis and give the analysis purpose and meaning. The narrative can reveal past errors and how people have handled those errors, which can give the organization more confidence to deal with future errors.

Ideally, the analyst and decision maker naturally create a narrative between them while discussing the issue. When a decision maker believes the analysis does not answer the correct questions or the analyst believes the decision maker is ignoring the analysis, this could indicate that the two participants failed to create a shared frame or a shared narrative. Formalizing the process of creating a narrative between the decision maker and analyst may help to bridge the gap between the decision maker and the analyst and help each individual learn from each other. Using the formal narrative structure proposed by narratologists, the analyst should seek to draw the narrative out from the decision maker. One way to understand the decision maker's narrative is to ask questions about what the decision maker hopes to achieve or what the decision maker thinks is important. The analyst should ask the decision maker to imagine a future desirable state and prompt the decision maker to state how this future could be achieved or could occur. Although defining a decision maker's goals and objectives is a method usually employed in hard systems thinking,[21] understanding a stakeholder's goals and objectives will prove helpful for constructing a soft systems narrative. Carefully worded questions can draw out the decision maker's thinking, goals, and objectives.

Value-focused thinking [87] is a method that encourages the decision maker to focus on values and objectives for a decision-making situation, which could be used to help structure a decision maker's narrative. An objectives hierarchy can provide a visual outcome of value-focused thinking by beginning with a decision maker's fundamental objective(s). As depicted in Figure 2, an objectives hierarchy contains the decision maker's fundamental objective or value at the top of the hierarchy and then breaks that fundamental objective into multiple sub-objectives.[56] Each sub-objective is further broken down into multiple criteria, and this process usually continues until the bottom level of objectives, which consist of measurable attributes. This objectives hierarchy can become the narrative that frames the analysis. Additional steps could be undertaken to write out a narrative in prose based on this objectives hierarchy. The analyst could sit down with the decision maker to ask questions about the narrative and construct an objectives hierarchy. A challenge to this process would be to ensure that the analyst is not unduly influencing the decision maker with biased questions and that the decision maker is not unduly influencing the analysis to fit his or her preconceived notions of the issue.

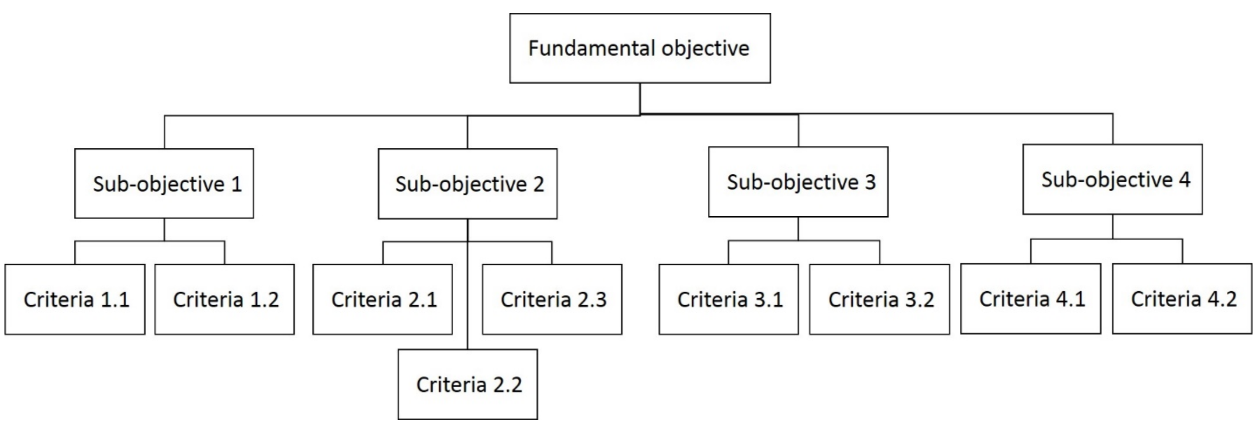

Figure 2. Objectives hierarchy

The narrative could inform the objectives hierarchy, or the objectives hierarchy could inform the narrative. Eliciting objectives from a decision maker often begins with questions such as "What do you care about?" or "What is most important to you?" or "What would you like to achieve in this situation?" After the decision maker answers that question of what is important to him or her, it might be necessary to ask for further details: "What do you mean by that?" Often, the top-level objectives are rather vague (e.g., effectiveness, quality, safety, beauty) so it is necessary to gain more specificity about those objectives.[88] Other strategies include having a decision maker develop a wish list, answering what makes an alternative good or bad, thinking more specifically about consequences or impacts and what makes them good or bad, and developing constraint-free thinking (what if there were no constraints?). If a decision maker has trouble explicitly stating those values or objectives, the decision maker could be prompted to simply speak about the decision issue as he or she understands it. The discourse could be the narrative as it likely will describe the challenges inherent in the decision issue and what the decision maker hopes to achieve. Occasionally, the analyst could interrupt the discourse in order to focus on the narrative. Listening and recording this narrative can begin the process of identifying the goals and objectives, which the analyst could begin to depict within an objectives hierarchy.

Alternatively, the objectives hierarchy could be used to construct a narrative in order to further communicate what the decision maker would like to achieve in this design issue. Values can be abstract and vague, but narratives can make those values more concrete.[89,90] The narrative would explain why those objectives are important to the decision maker and elucidate why the sub-objectives or attributes are connected to the top-level objectives. Keeney [87] provides an example of an objectives hierarchy resulting from a technical panel reviewing alternatives for transporting nuclear waste. The narrative resulting from such an objectives hierarchy as depicted in Figure 3 could be:

> Transporting nuclear waste is fraught with difficulties and challenges. The public is easily scared by the idea of radioactive material passing close to their houses or work areas. Another challenge is that if a transportation schedule is not coordinated correctly

with the nuclear facilities, spent nuclear fuel may not be transported and could build up at the facilities. This build-up of spent nuclear fuel might cause nuclear reactors to be shut down. A transportation solution must address these concerns. We need to show that the transportation solution is minimizing risk to the health and safety of the public and employees. If these concerns are not addressed, the solution will not be socially or politically acceptable. Keeping the costs of transporting nuclear waste low is also important to both the government and utilities. Unanticipated scenarios may arise in the future, and local decision makers will need the flexibility to be able to respond to these new events.

Although this narrative based on the objectives hierarchy does not provide the transportation solution, the narrative outlines the key issues that the decision makers are considering and explains why those issues are important to developing a good solution.

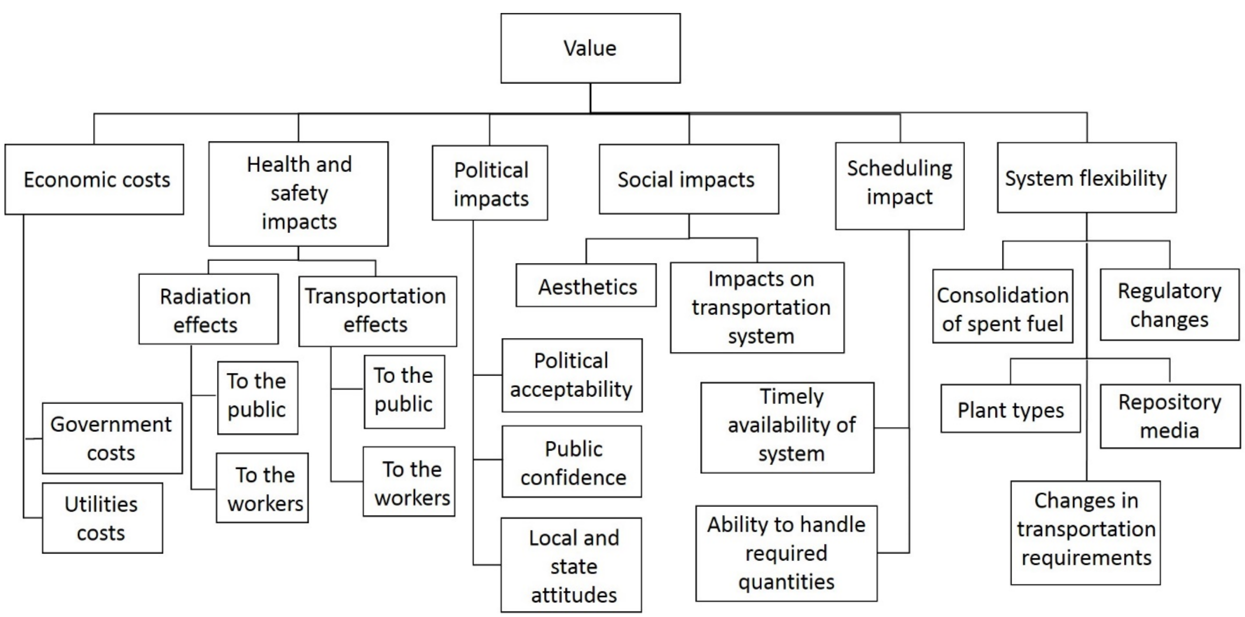

Figure 3. Objectives hierarchy for transporting nuclear waste [adapted from Keeney, 1996]

A decision maker may have explicit reasons for taking a certain position or for favoring a particular alternative. The analyst can draw the reasons out from the decision and use argument mapping to describe the rationale. Argument mapping visually depicts the logical structure of arguments (Figure 4). The conclusion of the argument presides at the top of the hierarchy, and the reasons in support of the conclusion flow from the conclusion. Objections to the conclusion are presented. Each reason is further supported by other reasons, evidence, and co-premises, and a rebuttal is stated for each objection. The process of mapping an argument to this specific structure can provide a context to incorporate a narrative or narratives for the analysis. Software is available to structure arguments within this type of method [91,92] and could be expanded to include a process to generate narratives. Artificial intelligence may develop further to manage and visualize evidence within the argument mapping method.[93]

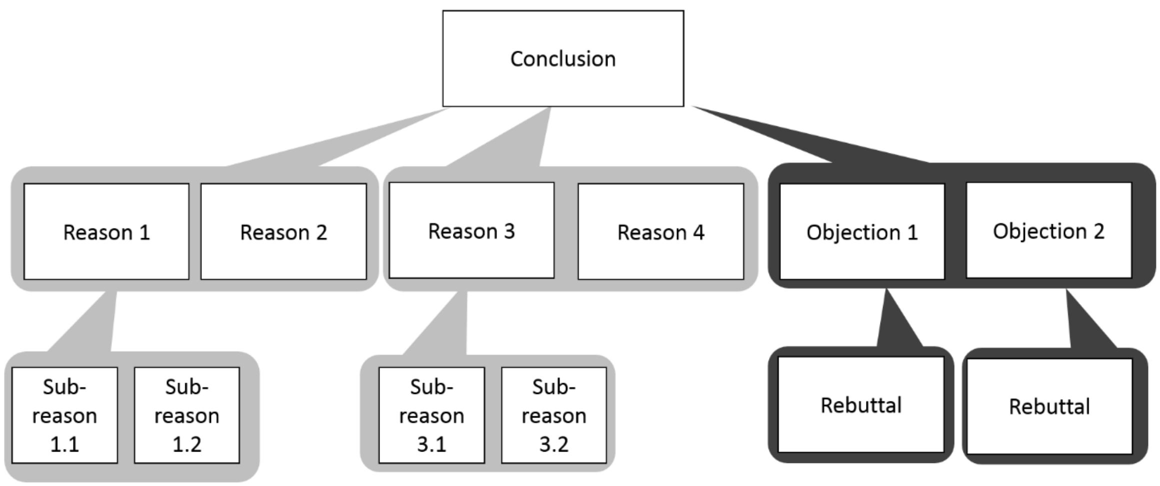

Figure 4. Argument mapping

Extending argument mapping to the integration of narrative within a complex systems engineering issue would mean that an individual's narrative would be structured so that his or her main conclusion or recommendation for the system would sit at the top of the structure. As with the objectives hierarchy, the narrative could be used to inform argument mapping or argument mapping could be used to inform the narrative. Some of the elements of the narrative (e.g., goal, conflict, resolution) align well with the concept of an argument mapping.

Encouraging a decision maker to identify the elements of the narrative can create the basic framework for argument mapping. The argument map can serve as a visual tool to capture and structure the decision maker's opinions as expressed via narrative form.

For example, assume an organization is considering how best to redesign its software for handling and recording financial transactions. One of the alternatives the organization may consider is commercial off-the-shelf (COTS) software.[94] An employee might describe why she favors purchasing COTS software with the following narrative:

> Using COTS software will enable our organization to interactively approve new financial transactions and the software can be purchased in six months. In fact, the software is currently available. It uses proven technologies. Our IT department is already familiar with the software, so there should not be a tremendous learning curve. The COTS software should meet our requirements because our requirements are pretty common for this type of software. Preliminary testing also indicates that the software will meet requirements.

However, another employee might express his objections to COTS software:

> The COTS software will not integrate very well with our current business process. I have seen many other organizations struggle with integrating COTS software into their business processes. This could disrupt our business operations because our employees are familiar with the existing software.

The first employee might respond: "We can mitigate the risk that the software will disrupt our business operations by providing training on the software before we implement it."

These narrative structures—which contain goals, settings, a conflict (e.g., whether COTS software will accomplish the goals), actions to overcome the conflicts (or mitigate the risk), and a possible resolution—could be embedded into an argument map, such as in Figure 5. The argument mapping provides a structure to the narratives and a visual means to depict the individuals' conflicting narratives. Similar to how a criminal investigator may test multiple theories of the case, the argument map can be examined to understand which narrative is best supported by the facts, requirements, and analysis.

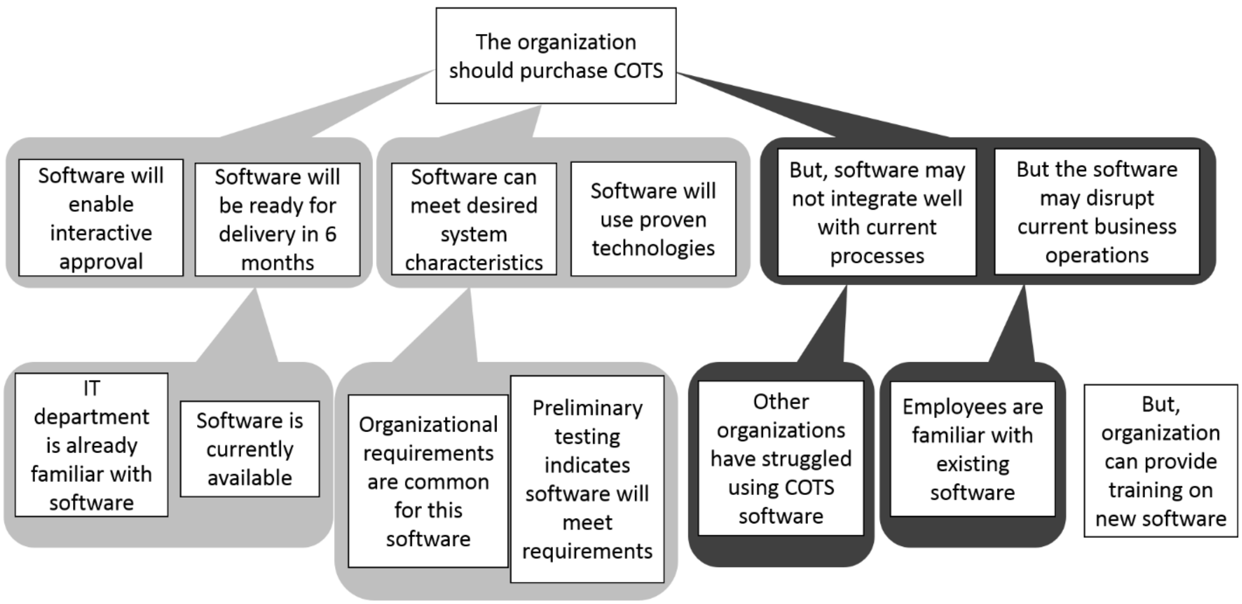

Figure 5. Argument mapping for purchasing commercial off-the-shelf (COTS) software [adapted from Tyree and Akerman, 2005]

The analysis can be presented to the decision maker through a narrative similar to the decision maker's original narrative frame. If the decision maker understands how the analysis can help him or her achieve his or her objectives or understand how the analysis feeds into his or her argument mapping, the decision maker will be more likely to understand the importance of the analysis and incorporate the analysis into his or her decision-making process. The analysis may also challenge the decision maker's existing narrative, which could lead to a situation of competing narratives: one narrative based on the decision maker's values and objectives and a second narrative grounded more in the analysis.

The manner in which the decision issue is framed within the narrative—whether this is the decision maker's original narrative or the narrative that develops from the analysis—will likely influence an individual's decision. Behavioral research has demonstrated how framing a decision can impact an individual's risk attitude, his or her preferences for trading off among multiple criteria or multiple objectives, and his or her susceptibility to heuristics and biases such as the sunk cost fallacy,[95] anchoring,[5] and representativeness.[5,96] Framing effects seem equally applicable to engineers as to non-engineers even though engineers generally have more technical training.[97] The narrative can also bias or unduly influence the decision maker.[98] Narratives can also bias individuals to believe one thing even if the data or statistics demonstrate another thing.[99,100]

If the analyst's narrative completely contradicts the decision maker's narrative, it is doubtful the decision maker will pay attention to the analysis even if the analytical narrative is grounded in objective truth and factual analysis. An analyst could create a narrative to reframe the analysis to align more closely with the decision maker's narrative in order to gain greater acceptance. People who express strong opinions about an issue generally tend to ignore or dismiss information that contradicts their strongly held beliefs.[101-103] Future research can explore the extent to which the narrative from the analyst should contradict a decision maker's biased prior narrative (which risks being ignored and rejected by the decision maker) or conform to the decision maker's prior narrative (which risks confirming the decision maker's previously held biased opinion). A potential solution may be for the analyst to use a narrative approach similar to the decision maker's original narrative in order to appeal to the decision maker.

Highlighting the significance of events and framing the issue through the use of narrative can facilitate better communication. Because narratives have closure, there is a moral meaning to the sequence of events, which causes these events to be significant as well as providing formal coherency [104] for decision makers. Creating narratives can help build relationships, thus fostering better communication. In a corporate culture, Denning [105] argues that telling stories can be useful for building relationships because storytelling is a natural and easy form of communication; stories are easy to remember, engage the emotions, and can help us understand complexity. Although using narratives may not always lead to a solution, they do provide a method for the difficult task of thinking about issue, and they provide a way to keep the decision makers engaged and even passionate about exploring the issue. The narrative can help keep the human content within the systems engineering problem.[21]

3.2. Build a narrative within a simulation

A natural way of incorporating narrative into the decision-making process is through simulation. Simulation is used in a wide variety of decision-making and systems engineering problems. Simulation has been used in design engineering for several decades, and increasingly, this effort is moving toward collaborative modeling and simulation methods.[106] Some simulations capture how people interact with engineered systems.[107] In virtual prototyping, designers use a simulated environment to determine if the design meets specifications.[108,109] Automobile manufacturers are using virtual prototyping,[110] and the Boeing 777 airplane was designed in this way.[111] The simulation of aerospace vehicles focuses on six-degrees-of-freedom motion.[112] System design, which often focuses on designing manufacturing processes and facility layouts, has greatly benefited from computer simulations.[113]

Simulations replicate a real-world situation in order to train decision makers, increase a decision maker's comfort level with situations, and allow a decision maker to make mistakes in a low-stakes environment. Narratives provide a context for how people make decisions with uncertainty,[114-116] and a narrative simulation can help decision makers understand that uncertainty.[117] A narrative simulation usually requires a user to read a story or description and then make decisions that will change the narrative and lead to different courses of action.[118] Because the outcome of the narrative can evolve in several different ways, this type of narrative simulation has been labeled as a branching narrative.[119,120] A well-constructed narrative simulation personalizes the environment and context for the user and can develop critical thinking skills.[118] Narrative simulation has been effective in preventing accidents, solving workplace issues, and promoting safety in farming and mining.[121-123]

Those who create narrative simulations for training decision makers can adapt concepts from video games. Video games are very popular and engaging in part because they have carefully constructed stories, and the players feel invested in the video game characters or stories. Video game narratives can unfold in different ways: linearly, by a branching narrative, or by an amusement park model in which players construct a story out of the various elements and subplots built into the game.[124] Immersion in video games can generate powerful psychological impacts, including physical presence, emotional presence, and narrative presence. Players' decisions shape the narrative within a video game, and increasingly, the players shape the narrative cooperatively.[125,126] A good narrative builds upon a user's real-world knowledge and provides intrinsic motivation for players to continue with the game.[127] A video game narrative provides rewards, and goals determine the rules of engagement.[127] Teaching decision-making skills is increasingly done within an online learning environment, and online learning games may provide better instruction than traditional classroom learning.[128] Video games designed for education or training require participants to strategize and hypothesize, and learning is enhanced if the learning content is integrated within a narrative plot.[129]

Designing a simulation that engages the decision maker through the use of narrative can be a good way to help the decision maker train in a particular situation, perhaps without even realizing he or she is learning through the simulation. Creative and engaging stories within a simulation enhances the training and learning process.[80] This simulation would envelop the decision maker and enable the decision maker to make decisions in a simulated environment. For example, some active shooter simulations place the participants in a 3D environment in which they attempt to remove the civilians and stop the shooter. These simulations create a realistic narrative that is memorable and also helps teach the participants how to think and react in an active-shooter situation. Swartout and van Lent [130] explore how narrative elements in a computer game could be used to design online educational and training. For example, a computer program called Bright IDEAS [131] uses an interactive drama to help mothers with cancer cope with stress and turmoil in their family.

Within the engineering design process, simulations are often used to help designers visualize a new product and understand how this product could be constructed and how it might be integrated within a larger system. A narrative simulation could present the broad contours of the design problem and then branch out in different ways according to different courses of action taken by the designer. The end result could be several design options, each of which is slightly different based on the designer’s decisions each time he or she enters into the narrative. Because the design of complex systems is typically a collaborative process, the simulation could be created to enable multiple designers to collaboratively shape the narrative. The system would need to be interactive, and the narrative would need to feel realistic. As technology develops in this area, the amusement park model could be applicable. According to this model, the simulation would have some basic design elements, building blocks, and subplots, and the system designer could incorporate these elements and subplots as necessary in order to construct the overall design that corresponds with the narrative that he or she wants to develop.

3.3 Promote consensus among multiple stakeholders

Narrative creation could also be used within the engineering design process in situations in which there are multiple decision makers to help them connect with each other and learn about the many features and interrelationships within a design problem, thus helping the decision makers work together to come up with good solutions. Wieck [85] points out that shared stories can provide people with a similar set of assumptions. Tsoukas,[132] in a discussion about uncertainty in organizations, explains that narratives are valuable for making sense out of the world around us because they present meaning as something that emerges rather than something that already exists. He also points out that new knowledge by way of narratives reminds us that what we see is not all there is, thus contributing to our perception of the complex nature of an organization. Bruner [133(p26)] remarks that narratives are a type of discourse that engages the reader's imagination in that the reader "writes" their own text under the guidance of the narrative text. A narrative enables the emergence of meaning by producing implicit rather than explicit meaning; providing stories from the perspective of the protagonist, thus furnishing a subjective perspective, and by providing multiple perspectives. Bucciarelli [4] argues that design is a matter of getting different people to have a common perspective and to agree on what needs to be done next.

In new and uncertain design contexts, dialogue and conversation among stakeholders help people define common goals or metrics for the new design so that everyone can understand. The narrative process can enhance individual and group learning. Conversations among each other that include relevant stories can help the engineering design team coalesce around a common concept and a shared vision. A shared narrative that the decision makers help construct will bind the decision makers to each other. The narrative should incorporate the decision makers' goals and objectives. It is preferable if the narrative is written down, and an individual will need to be responsible for explicitly writing down the shared narrative. This could be accomplished within a group setting or by having the individual separately elicit information from each of the decision makers.

When multiple decision makers or multiple stakeholders are involved with a project, they will have different opinions. Conflict will arise in part because each decision maker might have a different narrative. Conflicting narratives can prevent consensus building among decision makers, and the result is often unhappiness among some of the stakeholders with the selected decisions. Dialogic Design Science [15] provides the theoretical underpinnings to the Structured Dialogic Design Process, which is a methodology that encourages communication and consensus-building among stakeholders, especially in the context of democratic policy issues. The method deconstructs complex situations by framing questions and articulating observations through dialogue among members.[*] The narrative construct discussed in this paper could be integrated into this Structured Dialogic Design Process by having stakeholders express their narratives as part of the dialogue among participants.

A solution to conflicting narratives could be to have a facilitator who seeks to generate a shared narrative to which the conflicting parties can agree. This process would require the parties to first write down or provide their narrative for the situation. A facilitator could find common elements and seek to create a shared narrative based on those common elements. Or, the written

[*] https://www.futureworlds.eu/wiki/Dialogic_Design_Science

narratives could be shared with the other participants and the participants then could react to them. Even if the participants agree on a common narrative, the common narrative could reflect the participants' biases or groupthink. A facilitator should be cognizant of this possibility and seek to uncover biases or challenge assumptions and preconceived notions. It may be desirable to record multiple narratives and use a competing narrative to challenge biases held by one or more of the stakeholders.

The Delphi method,[134,135] which has been successfully used to generate consensus during expert forecasting, could be deployed as a method to create a shared narrative between engineers working on a design. The Delphi method is sometimes used as part of the Structured Dialogic Design Process that was referenced earlier. The Dephi method may also help individuals overcome their biases and be open to alternate explanations that challenge their preconceived notions.[134-137] The Delphi method requires that each participant individually write down his or her assessment or forecast, and those assessments are then shared anonymously with the other participants. The participants react to the assessment and provide comments, and then each participant can revise his or her assessment. The assessments and feedback continue for two to three rounds by which time participants frequently arrive at a consensus.

To apply the Delphi method to constructing a shared narrative, each stakeholder involved in the decision should write down their narrative of the issue without discussing it with the other stakeholders. Instructions should describe what is required in the narrative: (i) the goals or objectives of the issue, (ii) possible characters or agents in the decision issue, (iii) obstacles or challenges to the agent, and (iv) actions to take to overcome these challenges. The narratives should be mixed up among all of the stakeholders and read aloud so that each stakeholder is reading a narrative that they did not write. The stakeholders can comment on each narrative after it is read, describe points of agreement among narratives, and offer reasons why one narrative might not be valid. After hearing all of the narratives, each stakeholder will be asked to write down their narrative again while taking into account the narratives offered by the other stakeholders. The second round follows the format of the first round where each narrative is read aloud, and the author of each narrative remains anonymous. The stakeholders will have another opportunity to revise their narrative in light of hearing the other narratives.

Incorporating narratives in the decision-making process can also facilitate including lay people in the process. To aid public policy making, narratives have been used extensively to analyze the experiences of the citizenry. Epstein et al.[13] contend that including the narratives of lay citizens in making policy, especially regulatory, decisions is valuable. These narratives can reveal the complexity of various situations by exploring the tensions and disagreements inherent in many public policy and regulatory decisions. Narratives can uncover causes and other situations outside of an agency's authority that may adversely affect the effectiveness of a regulation. Narratives can also show unintended consequences that an agency had not intended as well as reframe the issue to highlight different circumstances around a public policy issue.

Although Epstein et al.[13] apply their discussion to involving lay people in making policy decisions, their reasoning could also be applied to involving lay people (where appropriate) in engineering decision making. For example, translating consumer preferences to requirements for engineering design can pose difficult challenges for the engineering community because of the differences in technical knowledge and the vocabulary used. Providing the means by which consumer narratives can inform the systems engineering design process could enhance engineering design and help designers better translate consumer preferences to technical requirements.

Involving lay people or consumers in the systems design engineering process is a relatively recent phenomenon. The process of including users at all stages of the product design and development lifecycle is gaining in popularity. This method permits quickly identifying issues and possible solutions, which leads to product improvement.[138] Engineering designers increasingly realize that it is important to involve consumers in the design process, including specifying the design and prototyping.[139] Quality function deployment is a process by which consumer preferences are translated to technical requirements for design and production.[58] Mashhadi et al.[140] analyzed consumer narratives relating their experiences in do-it-yourself repair projects of consumer electronics. This analysis can provide design firms with better insight into how to develop future product design features that correspond with consumer preferences.

4. Using Narrative to Improve Cookstove Design

An example focusing on designing cookstoves in the developing world can illustrate how narrative can improve decision making in engineering design. Over two billion people around the world use different types of biomass (e.g., coal, wood, dung) stoves for their daily energy needs, including cooking food and providing warmth.[141] These small cookstoves and three-stone fires can lead to a number of adverse health effects, including millions of premature deaths each year.[142] The use of these stoves and fires leads to deforestation and pollution, leading to adverse environmental impacts. Engineers, governments, and non-government organizations have been studying ways to build cookstoves that are safer, more efficient, and less harmful to the environment. Designing a better cookstove has been an active research project for at least 30 years. There is a lack of universally accepted standards and testing protocols for cookstoves,[143] and no established design algorithm for cookstoves in the developing world current exists.[144]

The requisite decision model for a design engineer is to design a cookstove that would likely be adopted in the developing world and for which funding agencies would support the production and distribution. The technical requirements for a cookstove may be: (i) the use of wood or charcoal for fuels as these are most widely available; (ii) portability; (iii) operable without a human watching it for at least 15 minutes; (iv) the generation of 0.3 kW to 2.1 kW of heat; (v) the ability to hold pots at a tilted angle; and (vi) easily repairable locally.[145] To satisfy these requirements, a mathematical model or multiple models need to characterize heat transfers and calculate emissions from the cookstove. The models would need to be validated across a wide range of operating conditions.[146,147] The goals for the decision model could be to maximize the likelihood of adoption in the developing world and to maximize the ability to get funding from agencies while satisfying the technical requirements.

Why is designing a cookstove for the developing world such a hard decision issue when it is fairly easy to meet the technical requirements? Part of the answer is that a solution involves many stakeholders who influence the cookstove design. Stakeholders include the design engineers, the funding agencies, government agencies, environmental groups, people on the ground working to improve development, and the people who will actually use the cookstoves. These stakeholders have different objectives, and these objectives may conflict with each other. The twin objectives of maximizing the likelihood of adoption and ability to get funding may be complicated by or depend on other objectives. These objectives include efficiency, user safety, health impacts, quality of life, energy consumption, environmental impacts, and cost. The engineer may want the most energy efficient cookstove. A group such as the World Health Organization may want a cookstove that leads to the best health outcomes for the community. Other groups may be more concerned about reducing energy consumption or developing a cookstove with the smallest environmental footprint. Funding agencies may put a premium on cost.

One way to identify and understand these objectives would be through the stakeholders' different narratives for the cookstove problem. A useful exercise would be to elicit narratives from each stakeholder to help drive the design and usage. The narrative for potential users of the cookstove in the developing world could be:

> I use a stove to cook food and warm my house. I can do this already by building small fires or having a constantly burning charcoal stove within my house. I don't have much money, and I'm not going to spend any money to buy a new cookstove when I currently have one that works for me. I have to watch my children constantly while cooking so that they do not burn themselves playing next to the stove. It would be nice to have a cleaner cooking area and a stove that is not as dangerous for my children. But, I don't know how to use a new stove. Even if somebody gives me a free stove, if it is too difficult to operate or to get fuel, then I am probably not going to use it. Plus, it will break at some point—then what?

A funding agency such as the World Bank might have a different narrative:

> We intend to spend $100 million over the next four years on designing and encouraging better cookstoves in the developing world. This critical and life-saving work will help to develop entrepreneurs in their countries and improve standards and technical knowledge. Our goal is to provide sustainable energy sources that improve health, enhance people's quality of life, and reduce environmental pollution. Better cookstoves will also empower women in the developing world. We want to fund innovative designs that will reduce

emissions and that are affordable, easy to use, and meet international guidelines.

Still, another stakeholder is an engineer who wants to research how to design and develop a better cookstove. Their narrative could be the following:

> Designing a better cookstove is important because this research provides important technology for the developing world. The solution needs to be technically sound but also economically feasible and culturally appropriate. Designing improved cookstoves would improve human health and the environment. I want to construct cookstoves with inexpensive materials that allow for a lot of natural air flow, but the design also needs to be robust without a lot of moving parts. For me to be funded for this type of project, I need to show how my research team's design is innovative and meets the funding agency's objectives. Because I am also interested in publishing my work in scholarly journals, I also need to demonstrate the uniqueness of my approach. I will need continued funding to support my research and my graduate students.

These three narratives could be summarized, as in Table II, according to the required elements of a narrative as introduced in Section 2.1. Understanding the stakeholders' narratives in this manner provides a method to analyze the similarities and differences across the different users.

Table II Three narratives for the cookstove design

	User narrative	**Funding agency narrative**	**Engineer narrative**
Goal	• Cook food • Warm house	Provide sustainable energy sources that • improve health • enhance people's quality of life • reduce environmental pollution	• Provide important technology for the developing world • Get research funded and published
Setting	• Subsistence living	Global concern (macro-	Engineering context

	• Lack of disposable income	view of the problem)	focused on technical solutions
Conflict	• Difficult to operate • Difficult to fix • Comfortable with the current open fire • But wants to protect children	• Many cookstove alternatives and NGOs • Hundreds or thousands of communities in developing world who could use a cookstove	Cookstove designs that are likely to be adopted may not be interesting research
Actions	• Adopt the new cookstove, or • Continue to use the old cookstove	Allocate money to non-profits, engineers, and companies for design and distribution of cookstoves	A lot of work and effort to design an innovative cookstove
Results	Ignore the new cookstove and continue using what she knows	Money spent on many different efforts with no real change in adoption of better cookstoves	Researches and designs a cookstove that is not used in the developing world

Understanding the stakeholders' narratives can provide the foundation for a shared narrative for arriving at a resolution around a cookstove design. The shared narrative would include the common elements among the stakeholders, such as the need for an easy-to-use, affordable solution. However, the differences in the three narratives are also key because the differences represent unique motivations for each stakeholder. The unique elements of each narrative need to be considered in order for each stakeholder to be invested in the new cookstove design. For the user to adapt a new cookstove, the cookstove design must have advantages over her current fire or stove that the user thinks are beneficial to her, and these particular benefits may not address environmental or health concerns. For the funding agencies, the cookstove design needs to help accomplish larger developmental goals such as mitigating climate change, growing the economy, and empowering women. The engineer responsible for designing the cookstove requires money to support a research team and the ability to pursue innovative research in cookstove design. Thus, understanding the different elements of each stakeholder's narrative provides insight into how a program for cookstoves could be developed that meets each of the stakeholder's objectives.

The narratives can also help motivate or drive the design algorithm. Different cookstove designs may be appropriate for different situations. The narratives could provide an indication for which situation calls for which cookstove design. With over two billion people potentially in need of improved cookstoves, their needs and demands could vary widely. It is impossible to acquire two billion narratives, but obtaining narratives from a broad representation of these two billion people could help designers to distinguish and categorize users according to their needs and requirements. Different design algorithms could be linked to each category or narrative. When deciding what type of cookstove design might fit best for a user, the narrative of the user could be used to categorize the user and provide insight into the type of design that best fits the user.

Given the many different stakeholders with different goals and objectives, it is important to understand how cookstove design impacts the stakeholders' goals and objectives. A systems-level model can integrate and connect different models that relate the cookstove design to these objectives. Individual components and design processes would serve as inputs into a behavioral model of user adoption.[148] Based on the user adoption model, a village energy model and an agronomic model (erosion, fertility, crop yield) can provide insight into how the cookstove design impacts all the objectives revealed via the narratives.[149] The stakeholder narratives can help inform the systems-level model to understand what outputs from the model would be helpful to stakeholders.

Encouraging adoption by users in the developing world remains one of the main difficulties with improving cookstoves. As described in Section 3.1, narrative can help connect a decision maker to the analysis. In the cookstove scenario, a potential user can represent a decision maker. However, the analysis and benefits of a newly designed cookstove may not be well understood by the user. A poor woman who is the mother of four children living in Ghana may not even care about some of the benefits such as mitigating climate change. To increase adoption of a newly designed cookstove, the engineers and the funding agencies must understand the users' narratives. One or multiple narratives (because there are multiple users) could capture the users' concerns and "requirements" for a cookstove design. After a cookstove is designed, a well-crafted narrative could be used to help instruct and convince users to adopt the new cookstove. If the users' narratives were used to inform the cookstove design, constructing a narrative that will encourage adoption of the new cookstoves will be easier.

5. Conclusion

Applying the narrative theory framework proposed here, this paper has presented a novel approach for how narrative can be successfully integrated into systems engineering and engineering design. The paper proposes three methods to improve engineering decision making using narrative. First, narrative can be used to understand a decision maker's goals and objectives and then use that narrative to make the analysis more appealing to the decision maker. Second, narrative can be integrated within computer simulations to help train decision makers. Third, eliciting narratives from different stakeholders in an issue can help create consensus by creating a shared narrative from the individual narratives.

An illustrative example outlined how narratives could help elucidate some of the challenges and differences in designing better cookstoves that will be used in the developing world. Understanding the narratives of different stakeholders can help foster greater understanding of their different goals and objectives. This understanding can lead to better design algorithms for cookstoves and greater acceptance and adoption by the user community.

However, the effect of implementing these methods has not been yet empirically tested. Future research could examine what challenges exist with implementing each of these methods and other ways that narrative can be integrated within engineering decision making (see Table I). Working with engineering companies to better understand, document, structure, and use their employees' narratives to solve complex issues can provide useful case studies and insight into the relationship between narrative and systems engineering. For example, storytelling among engineers in Cirrus Technologies (a British design and manufacturing firm) helps to create specific identities for products,[16] and IBM benefits from stories to learn how customers view its software products.[17]

Because a decision maker's narrative may conflict with the results of an analysis, future research could explore to what extent the analysis should align with the decision maker's narrative. For example, Betsch et al.[100] find that narratives seem to influence individual risk perception, but the use of numerical likelihoods appears to partially mitigate the bias effect. Integrating narrative within a simulation training program requires the ability to craft a narrative within an engaging computer program. Studies could measure the engagement of a user within a simulation based on the vividness of the narrative and the extent to which the user can shape the simulation narrative. When multiple people with different narratives have a stake in the decision, it may be difficult to achieve consensus or construct a shared narrative. Experimental studies could be performed to analyze how best to achieve convergence within systems engineering issues.

Systems engineering issues are typically very complex with many different elements and processes, and they involve multiple stakeholders and decision makers who make decisions over time. Narratives can be used to understand stakeholders' concerns and goals to enable framing the systems analysis in terms that these decision makers will understand and appreciate. Translating the analysis to a narrative can bridge the gap that can occur between the decision makers and the analysts. Such a framework could provide a foundation for better engineering designs and systems thinking among all participants.

Acknowledgements

This research was supported in part by the U.S. Department of Energy – Office of Fossil Energy under Contract No. DE-AC02-07CH11358 through the Ames Laboratory. The authors would like to acknowledge the very helpful feedback from Professor Kenneth M. Bryden at Ames Laboratory and Iowa State University and five anonymous reviewers.

References

1. White KP. Systems design engineering. Syst Eng 1998;1:285-302.
2. Hazelrigg GA. A framework for decision-based engineering design. Trans ASME J Mech Design 1998;120:653-658.
3. Thurston DL. Real and misconceived limitations to decision based design with utility analysis, J Mech Des 2001;123:176-182.
4. Bucciarelli LL. Reflective practice in engineering design. Design Stud 1984;5:185-190.
5. Tversky A, Kahneman D. Judgment under uncertainty: heuristics and biases. Science 1974;185:1124-1131.
6. Kahneman D, Slovic P, Tversky A, eds. Judgement under Uncertainty: Heuristics and Biases. Cambridge: Cambridge University Press; 1982. 576 p.

7. Beach LR. The Psychology of Narrative Thought: How the Stories We Tell Ourselves Shape Our Lives. Bloomington, IN: Xlibris; 2010. 196 p.

8. Beach LR. A New Theory of Mind: The Theory of Narrative Thought. Newcastle, UK: Cambridge Scholars; 2016. 210 p.

9. Prince G. Dictionary of Narratology. Rev. ed. Lincoln, NE: University of Nebraska Press; 2003. 126 p.

10. Bal M. Narratology: Introduction to the Theory of Narrative. 3rd ed. Toronto: University of Toronto Press; 2009. 256 p.

11. Abbott HP. The Cambridge Introduction to Narrative. 2nd ed. Cambridge, UK: Cambridge University Press; 2008. 270 p.

12. Dohan D, Garrett SB, Rendle KA, Halley M, Abramson C. The importance of integrating narrative into health care decision making. Health Aff 2016;35:720-725.

13. Epstein D, Heidt J, Farina C. The value of words: Narrative as evidence in policymaking. Evid Policy 2014;10:243–258.

14. Boddy D, Paton R. Responding to competing narratives: lessons for project managers. Int J Proj Manag 2004;22: 225–233.

15. Warfield JN. Science of Generic Design: Managing Complexity through Systems Design. Ames, IA: Iowa State Press; 1994. 588 p.

16. Lloyd P. Storytelling and the development of discourse in the engineering design process. Design Stud 2000;21: 357–373.

17. Gruen D, Rauch T, Redpath S, Ruettinger S. The use of stories in user experience design. Int J Hum Comput Interact 2002;14:503-534.

18. Madni AM. Towards a generalizable aiding-training continuum for human performance

enhancement. Syst Eng 2011;14:129-140.

19. Madni AM. Expanding stakeholder participation in upfront system engineering through storytelling in virtual worlds. Syst Eng 2015;18:16-27.

20. Szajnfaber Z, Gralla E. Qualitative methods for engineering systems: why we need them and how to use them. Syst Eng 2017;20:497-511.

21. Checkland P. From optimizing to learning: a development of systems thinking for the 1990s. J Opl Res Soc 1985;36:757-767.

22. Ronen R. Paradigm shift in plot models: an outline of the history of narratology. Poetics Today 1990;11:817–842.

23. Ryan ML. Narrative. In: Herman D, Jahn M, Ryan ML, eds. Routledge Encyclopedia of Narrative Theory. New York: Routledge; 2005:344-348.

24. Carroll N. Narrative closure. Philos Stud 2007;135: 1-15.

25. Todt O. The role of controversy in engineering design. Futures 1997;29:177–190.

26. Amason AC. Distinguishing the effects of functional and dysfunctional conflict on strategic decision making: resolving a paradox for top management teams. Acad Manage J 1996;39: 123–148.

27. Jones M, McBeth M. A narrative policy framework: clear enough to be wrong? Policy Stud J 2010;38:329-353.

28. McBeth M, Jones M, Shanahan E. Narrative policy framework. In: Sabatier PA, Weible CM, eds. Theories of the Policy Process. Boulder, CO: Westview Press; 2014:225-266.

29. Spoel P, Goforth D, Cheu H, Pearson D. Public communication of climate change science: engaging citizens through apocalyptic narrative explanation. Tech Commun Q 2008;18:49-81.

30. Shanahan EA, Jones MD, McBeth MK. Policy narratives and policy processes, Policy Stud J 2011;39:535-561.

31. Hinyard L, Kreuter M. Using narrative communication as a tool for health behavior change: a conceptual, theoretical, and empirical overview. Health Educ Behav 2007;34: 777-792.

32. Kreuter M, Green M, Cappella J, Slater M, Wise M, Storey D, Clark E, O'Keefe D, Erwin D, Holmes K, Hinyard L. Narrative communication in cancer prevention and control: a framework to guide research and application. Ann Behav Med 2007;33:221-235.

33. Murphy S, Frank L, Chatterjee J, Baezconde-Garbanati L. Narrative versus nonnarrative: the role of identification, transportation, and emotion in reducing health disparities, J Commun 2013:63:116-137.

34. Mateas M. A preliminary poetics for interactive drama and games. Digital Creativity 2001;12:140–152.

35. Louchart S, Aylett R. Narrative theory and emergent interactive narrative. Int J Contin Eng Educ Lifelong Learn 2004;14:506–518.

36. Hazelrigg GA. Validation of engineering design alternative selection methods. Eng Optim 2003;35:103-120.

37. Collopy PD. Aerospace system value models: a survey and observations. In: AIAA Space 2009 Conference & Exposition. Pasadena, CA: American Institute of Aeronautics and Astronautics; 2009. Available from: https://arc.aiaa.org/doi/pdf/10.2514/6.2009-6560.

38. Keeney RL, McDaniels TL. Value-focused thinking about strategic decisions at BC Hydro. Interfaces 1992;22:94-109.

39. Buede DM, Bresnick TA. Applications of decision analysis to the military systems

acquisition process. Interfaces 1992;22:110-25.

40. Gregory R, Keeney RL. Creating policy alternatives using stakeholder values. Manage Sci 1994;40:1035-1048.

41. Parnell GS, Conley HW, Jackson JA, Lehmkuhl LJ, Andrew JM. Foundations 2025: a value model for evaluating future air and space forces. Manage Sci 1998;44:1336-1350.

42. Parnell GS, Metzger RE, Merrick J, Eilers R. Multiobjective decision analysis of theater missile defense architectures. Syst Eng 2001:4:24-34.

43. Ewing Jr PL, Tarantino W, Parnell GS. Use of decision analysis in the Army Base Realignment and Closure (BRAC) 2005 military value analysis. Decis Anal 2006;3:33-49.

44. Gonzalez-Zugasti JP, Otto KN, Baker JD. Assessing value in platformed product family design. Res Eng Des 2001;13:30-41.

45. Carenini G, Poole D. Constructed preferences and value-focused thinking: implications for AI research on preference elicitation. In: Association for the Advancement of Artificial Intelligence (AAAI-02) Workshop on Preferences in AI and CP: Symbolic Approaches; 2002. Available from: https://www.aaai.org/Papers/Workshops/2002/WS-02-13/WS02-13-003.pdf.

46. Collopy PD, Hollingsworth PM. Value-driven design. J Aircr 2011;48:749-759.

47. Ross AM, Hastings DM, Warmkessel JM, Diller NP. Multi-attribute tradespace exploration as front end for effective space system design, J Spacecr Rockets 2004;41:20-28.

48. Balling R. Design by shopping: a new paradigm? In: Proceedings of the Third World Congress of Structural and Multidisciplinary Optimization (WCSMO-3) 1999;1:295-297.

49. Laouris Y, Michaelides M. Structured democratic dialogue: an application of a mathematical problem structuring method to facilitate reforms with local authorities in

Cyprus. Eur J Oper Res 2018;268:918-931.

50. Christakis AN, Warfield JN, Keever D. Systems design: generic design theory and methodology. In: Decleris M, ed. Systems Governance. Athens-Komotini, Greece: Ant. N. Sakkoylas; 1988:143-210.

51. Warfield JN, Cárdenas AR. A handbook of interactive management. Ames, IA: Iowa State University Press; 1994. 338 p.

52. Weigand K, Flanagan T, Dye K, Jones P. Collaborative foresight: complementing long-horizon strategic planning. Technol Forecasting and Soc Change 2014;85:134-52.

53. Laouris Y, Dye KMC, Michaelides M, Christakis AN. Co-laboratories of democracy: best choices for designing sustainable futures. In: Metcalf GS, ed. Social Systems and Design. Tokyo: Springer; 2014:167-183.

54. Dye KMC, Post D, Vogt EM. Developing a consensus on the accountability and responsibility for safe use of pharmaceuticals. White paper prepared for the National Patient Safety Foundation Workshop, June 10-11. Interactive Management Consultants; 1999. Available from: http://www.academia.edu/download/31195953/PharmasafetyWhitePaper.pdf.

55. Christakis AN, Dye K. The Cogniscope: lessons learned in the arena. In: Jenlink M, Banathy BH, eds. Dialogue as a Collective Means of Design Convention. New York: Springer; 2008: 187-204.

56. Hill JD, Warfield JN. Unified program planning. IEEE Trans on Syst Man Cybern 1972;5:610-621.

57. Hill Jr. RR. Decision support environment for concurrent engineering requirements. Technical paper. Air Force Human Resource Laboratory, Air Force Systems Command,

January; 1991. Available from: https://apps.dtic.mil/dtic/tr/fulltext/u2/a230899.pdf.

58. Chan LK, Wu ML. Quality function deployment: a literature review. Eur J Oper Res 2002;143:463-497.

59. Li H, Azarm S. Product design selection under uncertainty and with competitive advantage. J Mech Des 2000;122:411-418.

60. Chen W, Hoyle C, Wassenaar HJ. Decision-Based Design: Integrating Consumer Preferences into Engineering Design. London, UK: Springer Science & Business Media; 2012. 358 p.

61. Michalek JJ, Feinberg FM, Papalambros PY. Linking marketing and engineering product design decisions via analytical target cascading. J Prod Innov Manag 2005;22:42-62.

62. Antonsson EK, Otto KN. Imprecision in engineering design. J Vibration Acoust 1995;117:25-32.

63. MacDonald EF, Gonzalez R, Papalambros PY. Preference inconsistency in multidisciplinary design decision making. J Mech Des 2009;131:031009-0310022.

64. Jiao J, Zhang Y. Product portfolio planning with customer-engineering interaction, IIE Trans 2005;37:801-814.

65. McDaniels TL. The structured value referendum: eliciting preferences for environmental policy alternatives. J Policy Anal Manage 1996;15:227-251.

66. Gregory R, Wellman K. Bringing stakeholder values into environmental policy choices: a community-based estuary case study. Ecol Econ 2001;39:37-52.

67. Bailey K, Brumm J, Grossardt T. Towards structured public involvement in highway design: a comparative study of visualization methods and preference modeling using CAVE (casewise visual evaluation). J Geogr Inform Decis Anal 2001;5:1-15.

68. Wang J. Ranking engineering design concepts using a fuzzy outranking preference model. Fuzzy Set Syst 2001;119:161-170.

69. Xu ZS. Approaches to multiple attribute decision making with intuitionistic fuzzy preference information. Syst Eng Theory Pract 2007;27:62-71.

70. Chen X, Fan Z. Study on assessment level of experts based on difference preference information. Syst Eng Theory Pract 2007;27:27-35.

71. Aughenbaugh JM, Paredis CJ. The value of using imprecise probabilities in engineering design. J Mech Des 2005;128:969-979.

72. Payne JW, Bettman JR, Johnson EJ. Adaptive strategy selection in decision making. J Exp Psychol Learn 1988;14:534-552.

73. Shergadwala M, Bilionis I, Kannan K, Panchal JH. Quantifying the impact of domain knowledge and problem framing on sequential decisions in engineering design. J Mech Des 2018;140:101402-101414.

74. Shocker AD, Ben-Akiva M, Boccara B, Nedungadi P. Consideration set influences on consumer decision-making and choice: Issues, models, and suggestions. Mark Lett 1991;2:181-197.

75. Hu WL, Reid T. The effects of designers' contextual experience on the ideation process and design outcomes. J Mech Des 2018;140:101101-101118.

76. Miller SW, Simpson TW, Yukish MA, Bennett LA, Lego SE, Stump GM. Preference construction, sequential decision making, and trade space exploration. In: Proceedings of American Society of Mechanical Engineers (ASME) 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Portland, OR; 2013:V03AT03A014.

77. Buede DM. The Engineering Design of Systems: Models and Methods. 2nd ed. Hoboken, NJ: Wiley & Sons; 2009. 536 p.

78. Li Q, Chen YL. Modeling and Analysis of Enterprise and Information Systems. Berlin: Springer; 2009. 400 p.

79. Mayer RJ, Painter MK, deWitte PS. IDEF Family of Methods for Concurrent Engineering and Business Re-engineering Applications. College Station, TX: Knowledge Based Systems, Inc.; 1992. 77 p. Available from: http://www.iso.staratel.com/IDEF/BPR/IDEFFAMI.pdf.

80. Madni AM. Elegant systems design: creative fusion of simplicity and power. Syst Eng 2012;15:347-354.

81. Howard RA, Abbas AE. Foundations of Decision Analysis. Boston, MA: Pearson; 2016. 720 p.

82. Kusnic MW, Owen D. The unifying vision process: value beyond traditional decision analysis in multiple-decision-maker environments. Interfaces 1992;22:150-166.

83. Gass SI, Decision-aiding models: validation, assessment, and related policy analysis. Oper Res 1983;31:603-631.

84. George AL. Bridging the Gap: Theory and Practice in Foreign Policy. Washington, DC: U.S. Institute of Peace; 1993. 208 p.

85. Wieck KE. Organizational culture as a source of high reliability. Calif Manage Rev 1987;29:112–127.

86. Smith BH. Narrative versions, narrative theories. Crit Inq 1980;7:213-236.

87. Keeney RL. Value-Focused Thinking: A Path to Creative Decisionmaking. Cambridge, MA: Harvard University Press; 1996. 432 p.

88. Wall KD, MacKenzie CA. Multiple objective decision making. In: Melese F, Richter A, Solomon B, eds. Military Cost-Benefit Analysis: Theory and Practice. New York: Routledge; 2015:197-236.

89. Satterfield T, Slovic P, Gregory R. Narrative valuation in a policy judgment context. Ecol Econ 2000;34:315-331.

90. Shields DJ, Šolar SV, Martin WE. The role of values and objectives in communicating indicators of sustainability. Ecol Indic 2002;2:149-160.

91. Kirschner PA, Buckingham-Shum SJ, Carr CS, eds. Visualizing Argumentation: Software Tools for Collaborative and Educational Sensemaking. New York: Springer; 2003. 216 p.

92. van den Braak S. Sensemaking software for crime analysis. SIKS Dissertation Series No. 2010-12, the Dutch Research School for Information and Knowledge Systems; 2010. Available from: https://dspace.library.uu.nl/bitstream/handle/1874/40563/vandenbraak.pdf?sequence=2.

93. Bex FJ, Prakken H, Verheij B. Formalising argumentative story-based analysis of evidence. In: ACM Proceedings of the 11th International Conference on Artificial Intelligence and Law; 2007. Available from: http://www.florisbex.com/papers/ICAIL07.pdf.

94. Tyree J, Akerman A. Architecture decisions: demystifying architecture. IEEE Software 2005;22:19-27.

95. Vermillion SD, Malak RJ, Smallman R, Becker B, Sferra M, Fields S. An investigation on using serious gaming to study human decision-making in engineering contexts. Des Sci 2017;3:e15.

96. Wickham PA. The representativeness heuristic in judgements involving entrepreneurial success and failure. Manage Dec 2003;41:156-167.

97. Vermillion SD, Malak RJ, Smallman R, Fields S. Studying the sunk cost effect in engineering decision making with serious gaming. In: Gero J, Hanna S., eds. Design Computing and Cognition ’14. Cham, Switzerland: Springer; 2015:571-587.

98. Winterbottom A, Bekker HL, Conner M, Mooney A. Does narrative information bias individual's decision making? A systematic review. Soc Sci Med 2008;67:2079-2088.

99. Borgida E, Nisbett RE. The differential impact of abstract vs. concrete information on decisions. J Appl Soc Psychol 1977;7:258-271.

100. Betsch C, Haase N, Renkewitz F, Schmid P. The narrative bias revisited: what drives the biasing influence of narrative information on risk perceptions? Judgment Dec Making 2015;10:241-264.

101. Lord CG, Ross L, Lepper MR. Biased assimilation and attitude polarization: the effects of prior theories on subsequently considered evidence. J Pers Soc Psychol 1979;37:2098-2109.

102. Fischhoff B. Debiasing. In: Kahneman D, Slovic P, Tversky A, eds. Judgment under Uncertainty: Heuristics and Biases. New York: Cambridge University Press; 1982:422-444.

103. Weinstein ND, Klein WM, Resistance of personal risk perceptions to debiasing interventions. Health Psychol 1995;14:132-140.

104. White H. The value of narrativity in the representation of reality. Crit Inq 1980;7:5–27.

105. Denning S. The Leader’s Guide to Storytelling: Mastering the Art and Discipline of Business Narrative. 2nd ed. San Francisco: Josey-Bass; 2011. 368 p.

106. Sinha R, Paredis CJ, Liang VC, Khosla PK. Modeling and simulation methods for design of engineering systems. J Comput Inf Sci Eng 2001;1:84-91.

107. Monnier G, Renard F, Chameroy A, Wang X, Trasbot J. A motion simulation approach

integrated into a design engineering process. SAE Trans 2006;115:1118-11230.

108. Haas S, Jasnoch U. Cooperative working on virtual prototypes. In: Rix J, Haas S, Teixeira J, eds. Virtual Prototyping. Boston, MA: Springer; 1995:45-57.

109. Paredis CJJ, Diaz-Calderon A, Sinha R, Khosla PK. Composable models for simulation-based design. Eng Comput 2001;17:112-128.

110. Kumar S. Simulation, virtual prototyping for automotive applications. Auto Tech Rev 2017. Available from: https://autotechreview.com/features/simulation-virtual-prototyping-for-automotive-applications.

111. Upton J. Boeing 777. vol. 2, Airliner Tech Series. North Branch, MN: Specialty Press; 1998. 100 p.

112. Stevens BL, Lewis FL, Johnson EN. Aircraft Control and Simulation: Dynamics, Controls Design, and Autonomous Systems. 3rd ed. Hoboken, NJ: Wiley & Sons; 2016. 768 p.

113. Negahban A, Smith JS. Simulation for manufacturing system design and operation: literature review and analysis. J Manuf Syst 2014;33:241-261.

114. Rein M. Social Science and Public Policy. Harmondsworth, UK: Penguin Educational; 1976. 272 p.

115. Neustadt R, May E. Thinking in Time: The Uses of History for Decision Makers. New York: Free Press; 1986. 329 p.

116. Guhathakurta S. Urban modeling as storytelling: using simulation models as a narrative. Environ Plann B Plann Des 2002;29:895-911.

117. Regnier ED, MacKenzie CA. The hurricane decision simulator: a tool for Marine forces in New Orleans to practice operations management in advance of a hurricane. Manuf Serv Oper Manag 2019;21:103-120.

118. McCrary NE, Mazur JM. Conceptualizing a narrative simulation to promote dialogic reflection: using a multiple outcome design to engage teacher mentors. Educ Technol Res Dev 2010;58:325-342.

119. Gordon A, van Lent M, van Velsen M, Carpenter P, Jhala A. Branching storylines in virtual reality environments for leadership development In: Proceedings of the National Conference on Artificial Intelligence. Menlo Park, CA: AAAI Press; 2004:844-851. Available from: http://new.aaai.org/Papers/IAAI/2004/IAAI04-011.pdf.

120. Kapadia M, Falk J, Zünd F, Marti M, Sumner RW, Gross M. Computer-assisted authoring of interactive narratives. In: ACM Proceedings of the 19th Symposium on Interactive 3D Graphics and Games, San Francisco, CA: Association for Computing Machinery; 2015:85-92. Available from: https://cgl.ethz.ch/Downloads/Publications/Papers/2015/Zun15a/Zun15a.pdf.

121. Cole HP. Stories to live by: a narrative approach to health behavior research and injury prevention. In: Gochman DS, ed. Handbook of Health Behavior Research IV, Boston MA: Springer; 1997:325-349.

122. Cole, Cognitive-behavioral approaches to farm community safety education: a conceptual analysis, J Agric Saf Health 2002;8:145-149.

123. Morgan SE, Cole HP, Struttmann T, Piercy L. Stories or statistics? Farmers' attitudes towards messages in an agricultural safety campaign. J Agric Saf Health 2002;8:225-239.

124. Majewski J. Theorising video game narrative. Master's thesis. Centre for Film, Television & Interactive Media, Bond University; 2003. Available from: http://www.few.vu.nl/~A.Eliens/create/local/story/mthesis_jakub.pdf.

125. Ryan RM, Rigby CS, Przybylski AK. The motivational pull of video games: a self-

determination theory approach. Motiv Emot 2006;30:347-364.

126. Przybylski AK, Rigby CS, Ryan RM. A motivational model of video game engagement. Rev Gen Psychol 2010;14:154-166.

127. Dondlinger MJ. Educational video game design: a review of the literature, J Appl Educational Technology 2007;4:21-31.

128. Waraich A. Using narrative as a motivating device to teach binary arithmetic and logic gates. ACM SIGCSE Bulletin 2004;36:97-101.

129. Fisch SM. Making educational computer games educational. In: Proceedings of the 2005 Conference on Interaction Design and Children. Boulder, CO: Association for Computer Machinery; 2005:56-61. Available from: https://dl.acm.org/citation.cfm?id=1109548.

130. Swartout W, van Lent M. Making a game of system design. Comm ACM 2003;46:32-39.

131. Marsella SC, Johnson WL, LaBore C. Interactive pedagogical drama. In: Proceedings of the Fourth International Conference on Autonomous Agents. New York; 2000:301-308.

132. Tsoukas H. Complex Knowledge: Studies in Organizational Epistemology. Oxford: Oxford University Press; 2005. 426 p.

133. Bruner J. Actual Minds, Possible Worlds. Cambridge, MA: Harvard University Press, Cambridge; 1986. 222 p.

134. Linstone HA, Turoff M. The Delphi Method: Techniques and Applications. Reading, MA: Addison-Wesley; 1975. 620 p.

135. Ahn J, de Weck OL, Steele M. Credibility assessment of models and simulations based on NASA’s models and simulation standard using the Delphi method. Syst Eng 2014;17:237-248.

136. J. Rohrbaugh, Improving the quality of group judgment: social judgment analysis and the

Delphi technique. Organizational Behavior and Human Performance 1979;24:73-92.

137. Turoff M, Hiltz SR. Computer based Delphi processes. In: Adler M, Ziglio E, eds. Gazing into the Oracle: The Delphi Method and Its Application to Social Policy and Public Health. London: Jessica Kingsley Publishers; 1996:56-88.

138. Tang T, Lim ME, Mansfield E, McLachian A, Quan SD. Clinician user involvement in the real world: designing an electronic tool to improve interprofessional communication and collaboration in a hospital setting. Int J Med Inf 2018;110:90-97.

139. Kaulio MA. Customer, consumer and user involvement in product development: a framework and a review of selected methods. Total Qual Manage 1998;9:141-149.

140. Mashhadi AR, Esmaeilian B, Cade W, Wiens K, Behdad S. Mining consumer experiences of repairing electronics: product design insights and business lessons learned. J Clean Prod 2016;137:716-727.

141. International Energy Association. Energy poverty: how to make modern energy access universal? Paris: World Energy Outlook; 2010. Available from: www.worldenergyoutlook.org/media/weowebsite/2010/weo2010_poverty.pdf.

142. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, AlMazroa MA, Amann M et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the global burden of disease study 2010, Lancet 2013;380:2224-2260.

143. Simon GL, R. Bailis, J. Baumgartner, J. Hyman, and A. Laurent, Current debates and future research needs in the clean cookstove sector. Energy Sustainable Dev 2014;20:49-57.

144. Kshirsagar MP, Kalamkar VR. A comprehensive review on biomass cookstoves and a

systematic approach for modern cookstove design. Renewable Sustainable Energy Rev 2014;30:580-603.

145. Johnson NG, Bryden KM. Establishing consumer need and preference for design of village cooking stoves. In: ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; Portland, OR: American Society of Mechanical Engineers; 2013:V03AT03A042.

146. MacCarty NA, Still N, Ogle D. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. Energy Sustainable Dev 2010;14:161-171.

147. MacCarty NA, Bryden KM. Modeling of household biomass cookstoves: a review. Energy Sustainable Dev 2015;26:1-13.

148. Masera OR, Diaz R, Berrueta V. From cookstoves to cooking systems: the integrated program on sustainable household energy use in Mexico. Energy Sustainable Dev 2005;9:25-36.

149. Afrane G, Ntiamoah A. Comparative lifecycle assessment of charcoal, biogas, and liquefied petroleum gas as cooking fuels in Ghana. J Ind Ecol 2011;15:539-549.