A Systems Architecting Methodology Using Bloom's Taxonomy to Promote Creative Engineering Synthesis

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***Abstract*—Architecting complex systems requires high-level cognitive processing and extensive knowledge of the system elements, functions, relationships, and constraints. This paper describes a systems architecting methodology implemented through cognitive psychological creative processes using Bloom's taxonomy as a framework to generate the expert knowledge required to effectively and systematically synthesize new systems. Systems architecting activities were carried out to identify, develop, and capture factual and conceptual knowledge relevant to the system subject matter and functional elements, as well as to facilitate active processing of the knowledge through remembering, understanding, applying, analyzing, evaluating, and creating. Dual channel and limited capacity principles of learning were incorporated into the format of the systems engineering tools developed to assist with information processing and retention. Metacognitive strategies associated with memory and creative idea generation were implemented into the methodology to effectively and efficiently develop system alternatives using the full collection of knowledge. Synthesis of an orbiting sample capture and orientation system architecture to enable spacecraft-based on-orbit capture of a Mars sample container for a potential Mars Sample Return campaign was used as a case study.**

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1. INTRODUCTION

Modern engineering systems are rapidly becoming increasingly complex due to the development of new emerging technologies and the integration of elements that span multiple knowledge domains. Architecting new and effective systems with these attributes can require both a high level of creativity and a deep knowledge base stemming from multiple domains. Creativity within the field of engineering is typically implemented through idea generation processes and methodologies [1], [2], [3], variations in brainstorming techniques [4], [5], and varieties of algorithms and tools such as TRIZ [6]. Acquiring knowledge is typically accomplished through securing domain experts, spending time gaining experience, conducting literature review (e.g., utility and design patents), and reverse engineering (i.e. functional decomposition) of existing systems [7].

This paper aims to supplement these approaches and improve their effectiveness by structuring a methodology that further promotes creative engineering synthesis for architecting complex systems using a cognitive psychological approach based on current theories and principles of creativity, human cognition, and education, complimented with tools and techniques drawn from systems engineering. A strong focus of this research is on the education aspect, recognizing that expert domain knowledge is a key component of creativity and that incorporation of learning activities structured around Bloom's Taxonomy (a framework used by educators that classifies knowledge and cognitive processes) can assist with effectively acquiring necessary domain knowledge.

To illustrate the tools and methodology discussed in this paper, a Transfer Subsystem, which is an element of a Capture and Orient Module (COM), and part of a larger conceptual Rendezvous and Orbiting Sample Capture System (ROCS) described in [8] is used as a case study. The ROCS Capture and Orient Module concept was developed to enable spacecraft-based, on-orbit capture, orientation, and transfer of a Mars Orbiting Sample (OS) container into a containment vessel as part of a potential Mars Sample Return campaign (Fig. 1). The main function of the Transfer Subsystem is to assemble the OS into a Primary Containment Vessel (PCV), which seals off unsterilized Mars material to reduce the risk of exposing the Earth's biosphere to any potential Mars biology. One concept for the PCV consists of a set of PCV Lid and PCV Base hemispheres that can be linearly assembled around the OS (Fig. 2). The content used in the systems architecting methodology tool examples for the Transfer Subsystem in this paper was simplified from the content developed in the actual Transfer Subsystem architecting activities (discussed in [8]) to better help illustrate the layout of the tools, the intention of the tools, and the associated learning activities.

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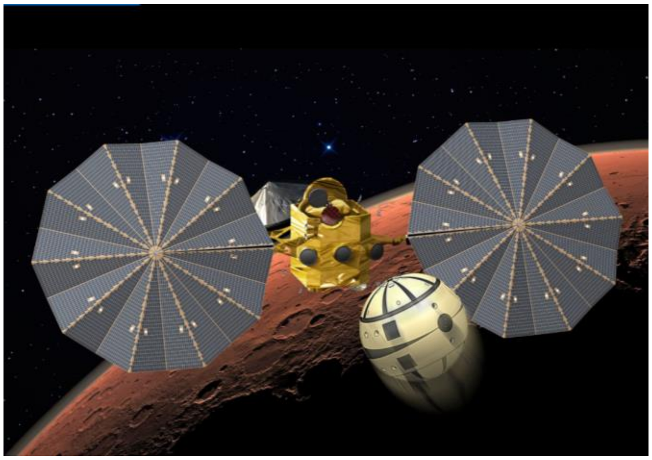


Figure 1. Artist's concept of Orbiting Sample (OS) capture in Mars orbit (Credit: D. Hinkle).

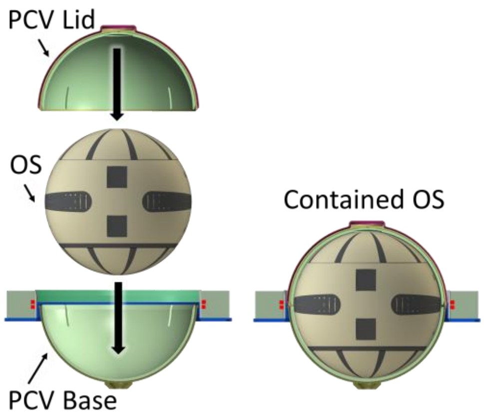


Figure 2. Assembly of the OS into the PCV.

2. BACKGROUND

System architecture, as defined in [1], is the embodiment of a system concept through the allocation of a system function to elements of form, along with the relationships among the system elements and surrounding context. Architecting a new system requires the architect to identify the functions of the system, acquire knowledge of physical elements that can effectively help perform the desired system functions, and possess the ability to structurally organize those elements into a new physical system that can successfully operate within the system environment and meet the needs of the stakeholders. Additionally, effectively planning, implementing, and managing systems architecting tasks benefits from the ability to precisely define and describe task objectives, task outcomes, and process tools.

Knowledge stemming from creativity research, cognitive psychology, education, and systems engineering was used to develop, define, and describe the systems architecting methodology in this paper. A brief description of relevant elements, principles, and concepts from these fields are described in this section.

Creativity

A focus of this research is to promote creativity in the architecting process through the development of a methodology. Prior to describing the methodology, a definition for creativity is first given, followed by a description of the creativity framework and creative process the methodology was built on.

Creativity Definition—The sociocultural definition for creativity stated by Sawyer in [9] was used: Creativity is the generation of a product that is judged to be novel and also to be appropriate, useful, or valuable by a suitably knowledgeable social group.

Creativity Framework—The creativity framework used is based on the 4 Ps framework proposed by Rhodes in 1961, which is composed of the creative Product, Person, Process, and Press [10], and is further defined in [9]:

- **Product:** The output of the creative Process determined to be novel and appropriate by the relevant social group.
- **Person:** The person who generates the creative Product, defined by their personality traits or personality types associated with creativity.
- **Process:** The processes involved during the creative work or creative thought.
- **Press:** External pressures acting on the creative Person or Process.

Creative Process—The particular stages in the creative process proposed by Sawyer in [9] are used:

1. Find and formulate the problem
2. Acquire knowledge relevant to the problem
3. Gather a broad range of potentially related information
4. Take time off for incubation
5. Generate a large variety of ideas
6. Combine ideas in unexpected ways
7. Select the best ideas
8. Externalize the idea using materials and representations

Cognitive Psychology

Cognitive psychology is the branch of psychology concerned with the scientific study of the mind [11]. Understanding of the mind, how knowledge is stored, limitation in the various memory stores, and problem solving blocks were used to help construct the learning activities applied in the architecting methodology and are briefly discussed below.

Memory—A multi-store model of memory composed of three separate memory systems was assumed [12], [13], [14]:

- **Sensory:** Brief memory storage for the senses, such as visual (iconic) and auditory (echoic) information.

- **Short-term:** Brief memory storage of small amounts of information over the periods of a few seconds. Short-term memory is used for temporary maintenance and manipulation of information while performing complex tasks as a part of working memory. Short-term memory capacity for adults is estimated to be three to five chunks of information (i.e. a collection of concepts with strong associations) [15].

- **Long-term:** Memory storage capable of holding information for long periods of time. Long-term memory is composed of declarative memory, which is retrieved consciously, and nondeclarative memory, which is retrieved through performance. Fig. 3 shows a general classification of long-term memory types.

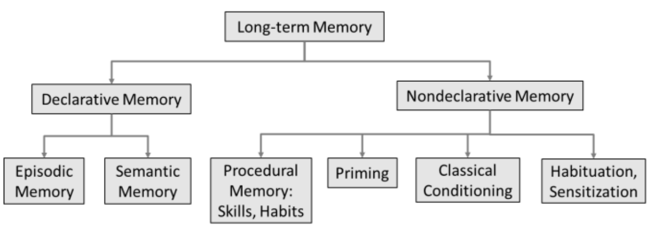


Figure 3. Classification of long-term memory types [12], [16].

Working Memory—A system concept for memory that encompasses both short-term memory storage along with associated mental processes consisting of the central executive, phonological loop, visuo-spatial sketchpad, and episodic buffer [17].

- **Central Executive:** Component of working memory that carries out attentional focus, division of attention, task switching, and other cognitive processes. Further discussion of the central executive cognitive control of behavior, such as controlled updating of short-term memory, setting goals, planning, task switching, stimulus attention, and response inhibition, is provided in [18].

- **Phonological Loop:** Component of working memory responsible for temporary maintenance of acoustic or speech-based information.

- **Visuo-spatial Sketchpad (VSSP):** Component of working memory responsible for temporary maintenance of visual and spatial information of objects. The VSSP is composed of object memory, which remembers what the objects are (e.g., shapes, sizes, and colors), and spatial memory, which remember where objects are [14]. Using these types of memory, a person can mentally manipulate objects, as an engineer might do to mentally assemble components and imagine the operation of a physical system. The capacity limit of visual short-term memory is estimated to be around four objects [19].

- **Episodic Buffer:** Component of working memory that holds integrated chunks of information from sensory memory, short-term memory, and long-term memory. The episodic buffer plays a role in perceptually and creatively binding different sources of information together into new chunks.

Episodic Memory—Episodic memory is a type of declarative long-term memory used to store past personal experiences or episodes occurring at a specific time and place [12]. Episodic memory can be a primary component of autobiographical memory, which stores information about events and experiences of personal significance.

Semantic Memory—Semantic memory is a type of declarative long-term memory used to store general information about the world involving facts (words and definitions), concepts (mental representations of categories of objects or items), and schemas (structured chunks of information) [12]. Schemas include scripts, which also incorporate sequences of events. Information stored in semantic memory may be associated with autobiographical memories (i.e. personal semantic memories) [11].

Problem Solving Blocks—Common psychological barriers to problem solving include irrelevant information, functional fixedness, mental set, and unnecessary constraints [20].

- **Irrelevant Information:** Focusing on information not relevant to the problem can send the problem solver down the wrong path. The psychological process of selective encoding of relevant information from irrelevant information is a key component of insight, which is considered by Sternberg et al. to be an important mental skill for dealing with novel tasks and situations [21].

- **Functional Fixedness:** Perception of an object only in terms of its most common use. This limits the ability to imagine new uses and approaches that may be useful to solve the problem.

- **Mental Set:** Using "tried and true" problem-solving strategies or solutions that have worked in the past. Mental set can lead to rigid thinking, which may interfere with effective problem solving and inhibit consideration of novel solutions.

- **Unnecessary Constraints:** Assuming constraints that do not exist. Overconstraining the problem can make the problem more difficult or impossible to effectively solve.

Education

Principles of Learning and Bloom's Taxonomy are two concepts from the field of education that are applied in the architecting methodology.

Principles of Learning—Three research-based principles from the science of learning are discussed in [22] and summarized below:

- **Dual Channels Principle:** People possess two separate channels, a verbal and a visual, to process information. Representing incoming information both visually and verbally can improve comprehension and retention.

- **Limited Capacity Principle:** People can only process a small amount of information in each channel at any one time due to storage limitations in their working memory. Encoding information into chunks can provides a means for people to have access to more information in their working memory. Additionally, reducing extraneous information can make more working memory available for processing the more relevant, essential information.

- **Active Processing:** Meaningful learning occurs when people actively engage in cognitive processing of the information through proper selection (i.e. focusing attention onto), organization (i.e. mentally organizing and representing the information verbally and pictorially in working memory), and integration with prior knowledge (i.e. knowledge in long-term memory).

Bloom's Taxonomy—Bloom's Taxonomy is a framework that classifies knowledge and cognitive processes into categories. The taxonomy is used by educators to precisely construct and categorize instructional objectives, as well as to align learning activities and assessment tasks with those objectives. The taxonomy was first published by Bloom in 1956 [23], and then revised by Anderson et al. in 2001 [24]. The full set of categories and subcategories for the knowledge and cognitive process dimensions of the revised Bloom's Taxonomy are shown in Tab. 1, and summarized below.

Categories of the knowledge dimension include:

- **Factual:** Discrete, isolated content elements, such as terminology and symbols, specific details, and basic elements of a discipline.

- **Conceptual:** Interrelationships among basic elements within a larger structure (e.g., schemas) that function as a system, as well as other disciplinary knowledge, such as classifications and categories, principles and generalizations, and theories and models.

- **Procedural:** Knowledge of processes, such as subject-specific skills and algorithms that end in a fixed result, subject-specific techniques and

Table 1: Bloom's Taxonomy matrix with x's indicating classifications of the instructional objectives in the presented systems architecting methodology.

					Cognitive Process																		
				Category	1 Remember		2 Understand							3 Apply		4 Analyze			5 Evaluate		6 Create		
		Category		Subcategory	1.1 Recognizing	1.2 Recalling	2.1 Interpreting	2.2 Exemplifying	2.3 Classifying	2.4 Summarizing	2.5 Inferring	2.6 Comparing	2.7 Explaining	3.1 Executing	3.2 Implementing	4.1 Differentiating	4.2 Organizing	4.3 Attributing	5.1 Checking	5.2 Critiquing	6.1 Generating	6.2 Planning	6.3 Producing
Knowledge	A	Factual	A.A	Terminology	X																		
			A.B	Specific Details/Elements	X			X	X	X	X					X				X			
	B	Conceptual	B.A	Classifications/Categories		X			X														
			B.B	Principles/Generalizations			X	X								X				X			
			B.C	Theories/Models/Structures																X			
	C	Procedural	C.A	Subject-specific Skills/Algorithms																			
			C.B	Subject-specific Techniques/Methods					X	X										X	X		
			C.C	Criteria for Procedure Use																			
	D	Metacognitive	D.A	Strategies																			
			D.B	Cognitive Tasks																			
			D.C	Self-knowledge																			

methods, and criteria for selection and use of appropriate procedures.

- **Metacognitive:** Knowledge of cognition and awareness of one's own cognition, such as strategies and heuristics, knowledge of cognitive tasks and conditional knowledge on when to use different strategies, and self-knowledge of one's capabilities and motivational beliefs.

Categories of the cognitive process dimension include:

- **Remember:** Retrieving relevant knowledge from long-term memory. Examples include recognizing knowledge similar with the presented material and recalling knowledge when prompted.

- **Understand:** Constructing meaning from instructional messages through integration of new knowledge with existing schemas and cognitive frameworks. Examples include interpreting (converting knowledge from one form to another), exemplifying (providing specific examples of a concept or principle), classifying (determining something belongs to a particular category based on a general concept or principle), summarizing (constructing a representative statement of given information or abstracting a general theme), inferring (finding a pattern amongst a set of instances or drawing a conclusion), comparing (detecting similarities or differences between objects or ideas), and explaining (constructing a cause-and-effect model of a system).

- **Apply:** Carrying out a process or procedure. Examples include executing a skill or algorithm to perform a familiar task (i.e. an exercise), as well as implementing a technique or method to perform an unfamiliar task (i.e. a problem).

- **Analyze:** Breaking down a system into its basic elements, determining the relationships between the elements, and then determining the underlying purpose of the system. Examples include differentiating relevant from irrelevant system elements, structurally organizing elements in a system, and attributing intent to a system.

- **Evaluate:** Judging based on criteria and standards. Examples include checking a system for internal inconsistencies or fallacies, as well as judging a system based on external criteria.

- **Create:** Reorganizing elements together into a novel pattern or structure to form a new product. Examples include representing the problem and generating possible new solutions, devising a plan to implement a new solution, and executing a solution plan to produce a new product.

Systems Engineering

According to [25], systems engineering guides the engineering of complex systems, where a system is a set of interrelated elements working together toward a common objective. Systems engineering methods for concept generation, along with various systems engineering tools, were used for developing the methodology presented in this paper.

Concept Generation—Various frameworks for generating system concepts exist and are described in [1], [7], [25], and [26]. In general, most follow a similar flow of requirements analysis, functional definition, physical definition, and design validation. In particular, aspects of the four-step concept ideation framework outlined in [1] and described below were applied in the methodology:

1. **Develop the Concepts:** This step includes defining the problem statement goals, defining the solution-neutral functions, developing solution-specific concept options, and verifying that the concepts meet the problem statement goals.

2. **Expand the Concepts and Develop the Concept Fragments:** This step includes functionally decomposing the concepts into principle internal functions (if necessary) and developing concept fragments (i.e. concept elements) for these internal functions (following the same procedure in Step 1).

3. **Evolve and Refine the Integrated Concepts:** This step includes reviewing the concepts and concept fragments to ensure sufficient coverage of the trade space and combinatorially recombining fragments to create new concepts.

4. **Select a Few Integrated Concepts for Further Development:** This step includes down-selecting the concepts based on backward considerations (probability of satisfying the goals) and forward considerations (probability of producing a good architecture), as well as reformulating the problem statement goals if the selected concepts cannot sufficiently meet them.

Tools—Systems engineers use a variety of tools to help document, analyze, evaluate, and develop complex systems. Elements of the following tools were used to develop the toolkit for the methodology discussed in this paper:

- **Morphological Matrix:** A matrix that lists integrated system concepts along one axis and concept fragments (i.e. concept elements) along the other. The concept fragments that compose each integrated system concept are indicated in the matrix. The morphological matrix can be used to represent and organize system configuration alternatives. Morphological matrices are discussed further in [1].

- **Design Structure Matrix:** A matrix that lists system components on both axes. Connections from components flowing from one axis to each component on the other axis are indicated in the matrix. The design structure matrix can be used to show spatial, topological, and connectivity relationships between system components. Design structure matrices are discussed further in [1].

- **House of Quality Diagram:** A diagram developed through the Quality Function Deployment (QFD) method that captures the customers, customers' requirements, system concept alternatives, relationships between the system concepts and requirements, target engineering specifications, and interdependencies of engineering specifications. The method can be effective at collecting and refining functional requirements from the customer. House of Quality Diagrams and the QFD method are discussed further in [7] and [27].

- **Decision Matrix:** A matrix developed through the Pugh method that captures and scores system concept alternatives (listed along one axis) over a set of criteria (listed along the other axis with weights). Scores are provided for each alternative over each criteria within the matrix. A total weighted score is calculated and reported for each alternative. Decision matrices, the Pugh method, and alternate decision matrices and methods are discussed further in [7], [26], and [28].

3. Systems Architecting Approach

The systems architecting methodology proposed in this paper was constructed around a 6 Ps Creativity Framework, which was built upon the 4 Ps framework (Product, Person, Process, Press) proposed by Rhodes in [10]. Additionally, the methodology acknowledges that creativity stems from domain expertise, as well as higher levels of cognitive processing. The 6 Ps Creativity Framework, along with the use of Bloom's Taxonomy to generate expert knowledge and implement higher levels of cognitive processing, are described in this section.

6 Ps Creativity Framework

A 6 Ps framework consisting of three physical elements (Press, Person, and Products) and three interactions (Process, Proof, and Promotion) was developed to form the foundation for the creativity methodology described in this paper (Fig. 4). It was based on the 4 Ps creativity framework, but extended to more clearly distinguish the physical elements from the interactions between those elements. The interaction names were based off of the primary activities that contribute to the final generation and acceptance of the creative Product. Additionally, for each interaction, a feedforward flow and feedback flow was identified to indicate which elements initiate and respond to the activities carried out within these interactions.

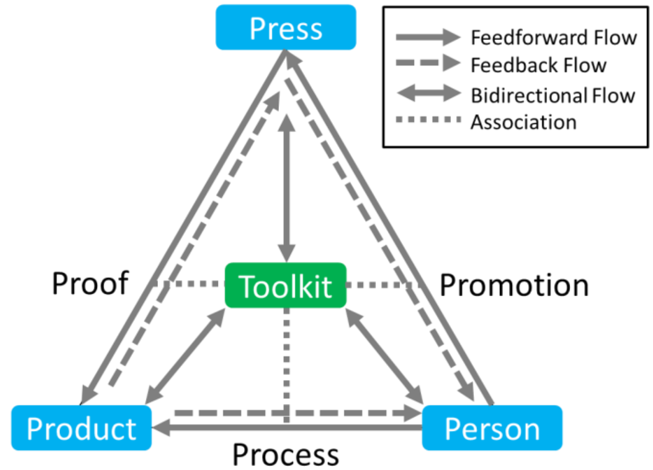


Figure 4. 6 Ps Creativity Framework.

The physical elements Product, Person, and Press:

- **Product:** The artifact (i.e. manufactured object), process, system, or service produced, as described in [2]. Based on the definition of creativity mentioned earlier, the Product must be both novel and useful relative to the problem it is intended to solve to qualify as creative.

- **Person:** The individual creating the Product. Associated with the Person are their personal attributes, such as knowledge, experience, intelligence, personality, motivation, mood, and feeling. Personal attributes in the context of creativity are discussed in [2], [9], and [29]. The individual may be part of a design team or organization.

- **Press:** The external elements that interact with the Person and Product. This research includes product stakeholders as part of the Press, which are considered the people (e.g., users, customers, or clients) that hold an interest in the Product and can impact its development within the associated organizational, social, and cultural environment. The stakeholders possess the needs, requirements, desires, and expectations that define the Product. They may play the role of the suitably knowledgeable social group that is critical to evaluating and accepting the creative Product, which is a key component to the sociocultural definition of creativity.

The interactions Process, Proof, and Promotion:

- **Process:** The mental processes carried out by the creative Person that lead to the synthesis of the creative Product. Action theory, where the execution of the creative work is essential to the creative process [9], is assumed for defining this process. Feedforward flow is the Product development, while feedback flow is the verification of the Product. This feedback helps the Person assess the state of the Product and its performance relative to the design criteria.

- **Proof:** The use of the Product by the Press for the purpose of validating its operation. Feedforward flow is the stakeholder's use or perception of the Product (either the Product itself, or a physical/virtual prototype of the Product) in order to test the Product and assess how it meets their needs, requirements, desires, and expectations. Feedback flow is the validation of the Product from the testing or assessment. This feedback informs the stakeholders of the Product's capabilities and limitations, which can help recalibrate stakeholder expectations of the Product, as well as lead to the creation or discovery of new requirements and use cases.

- **Promotion:** The activity carried out by the Person to encourage adoption of the Product by the Press. Feedforward flow is the promotional pitch of the Product to the Press to inform them of the Product and its capabilities, persuade them to choose and adopt the Product (potentially amongst competing alternatives), and remind them of the Product to maintain awareness of it. This activity draws from the marketing definition of Promotion, which is to inform, persuade, and influence the consumer's purchase decision [30]. Feedback flow is a design review, providing stakeholder input to the Person about the Product and its development. For Promotion to be most effective, it should be tailored to both the specific individual promoting the Product and the specific stakeholder (e.g., the particular market segment) it is directed towards.

The Toolkit contains the tools and materials used by the Person, Press, and Product to carry out the Proof, Promotion, and Process activities. These tools may capture information, assist with learning, and facilitate information transfer. Therefore, the bidirectional flows shown in Fig. 4 between the Toolkit and the three surrounding elements (Person, Product, and Press) may be considered learning.

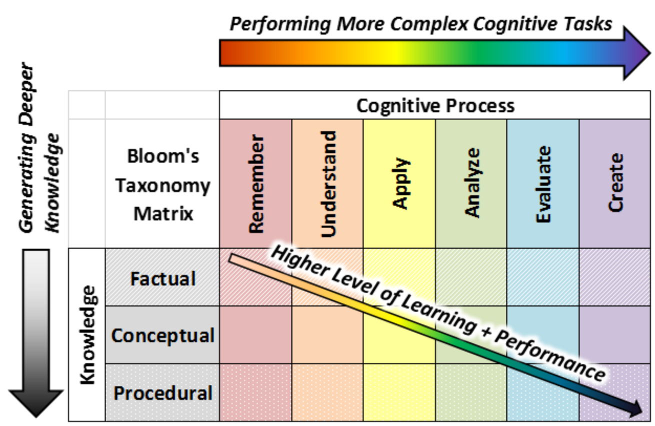
Within the context of systems architecting, this research focuses on the creative synthesis (Process) of a novel system architecture (Product), carried out by a system architect (Person), for specific stakeholders (Press), though the use of a set of learning tools (Toolkit). Product Promotion and Proof are also acknowledged as key contributors to successfully producing the creative Product, but are not the primary focus of the methodology discussed in this paper.

The methodology is structured around a Toolkit composed of tools derived from systems engineering tools, carried out through a Process based on creativity research, with an emphasis on knowledge generation using principles of learning from educational psychology, while acknowledging cognitive constraints and problem solving blocks identified from cognitive psychology research.

Knowledge Generation using Bloom's Taxonomy

A constructivist learning approach to promote meaningful learning and generate deeper knowledge that can be transferred to synthesize new system architectures was taken. The approach generates deeper knowledge and elicits more complex thinking through methodically implementing learning activities that incrementally increase in both complexity of knowledge and cognitive processing using the Bloom's Taxonomy framework (Tab. 2). This strategy is based upon research showing that deeper processing strengthens memory traces in long-term memory [31]. Specialized tools were developed, along with associated procedures, to implement these learning activities during the architecting process. The overall sequence in which these learning tools are implemented was structured around the eight creativity stages proposed by Sawyer in [9]. Within each tool, the subcategories of Bloom's Taxonomy were used to classify the instructional objectives and the generated knowledge to a level of specificity that can help promote effective communication, understanding, implementation, analysis, evaluation, and improvement of the tools.

Table 2. Progression of knowledge generation and cognitive processing along Bloom's Taxonomy to enable a higher level of learning and performance.



Several learning activities call for the selection or generation of new terms (e.g., categories, elements, functions, and approaches). To facilitate the encoding of new terms into long-term memory, instructions were given to make the terms (if possible) short (easier and quicker to rehearse within the phonological loop [18]), distinct in sound and meaning (to help avoid the phonological similarly effect that affects recall of similarly sounding verbal material [14] and interference in semantic memory from learning terminology with similar meanings), comprehensive (new information is easier to remember the better it can be related to prior knowledge [18]), and concrete (concrete terms help to activate relevant prior knowledge and recall concrete schemas from long-term memory that provide useful analogies to support meaningful learning through the process of elaboration [32]).

Several learning activities call for grouping items into categories. For these activities, instructions were given to group items into no more than five. Doing so enables cognitive processing of items within the category (e.g., comparative analysis) by keeping the number of items in short-term memory within the memory capacity of five chunks, as well as facilitates the development of new chunks composed of the items within the category. Creating chunks can aid in long-term memory encoding and retrieval, reduce cognitive load when processing the information, and provide a means to access more information in working memory when the chunks are recalled.

4. SYSTEMS ARCHITECTING TOOLS

Tools developed for the methodology are described in this section. For each tool, an educational objective, brief description, overall layout, and procedure for use are provided. Blocks of information within the layout are numbered based on the recommended order to complete them. Blocks that represent a learning activity are color-coded in the layout and classified with Bloom's Taxonomy based on their learning objectives, which are listed in a separate table. Blocks that are colored gray and not listed in the table are merely for reference and do not have a specific instructional objective associated with them (though this information may be used for other learning activities). For each instructional objective, the specific cognitive process and knowledge subcategory are provided in parenthesis for reference. For example, an instructional objective that consists of classifying (Cognitive Process subcategory 2.3 in Tab. 1) techniques (Knowledge subcategory C.B in Tab. 1) is notated as "(2.3-C.B)". Additionally, for each instructional objective, the learning outcome in terms of knowledge generated is specified, along with its knowledge subcategory in parenthesis.

Function Tree

Educational Objective—Ability to provide examples of specific functional techniques to achieve the overall system operational objective.

Tool Description—This tool interprets the system operational objective in terms of a basic general function. A tree consisting of possible functional techniques branch from the general function. This tool helps develop a deeper understanding of the system operational objective and communicates possible techniques to perform the function. This tool generalizes the operational objective to help disassociate preconceived solutions that may limit creative thinking and allows for redefinition and reframing of the problem in different ways to help with the search, identification, generation, and classification of additional system concept solutions. Fig. 5 and Tab. 3 show the layout of the Function Tree and associated instructional objectives classified using Bloom's Taxonomy. Fig. 6 provides an example for the Transfer Subsystem.

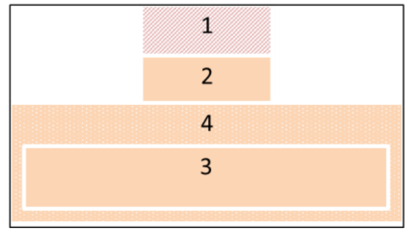


Figure 5. Function Tree layout labeled by step.

Table 3. Function Tree classification of objectives labeled by step.

		Cognitive Process					
	Bloom's Taxonomy Matrix	Remember	Understand	Apply	Analyze	Evaluate	Create
Knowledge	Factual	1					
	Conceptual		2,3				
	Procedural		4				

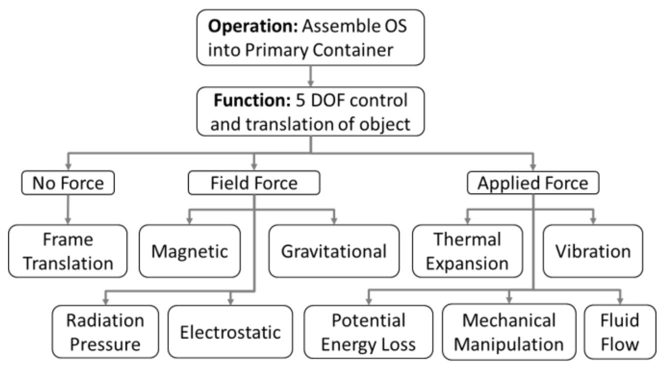


Figure 6. Example Function Tree.

Steps:

1. **Instructional Objective:** Identify the system operational objective (1.1-A.B).

   Activity: Write the specific details of the operation required of the system. The operational objective defines what the system needs to accomplish from the perspective of the stakeholder. Concisely defining the core operational objective separates out relevant information from irrelevant information, helping to identify and focus attention on the core problem to be solved.

   Knowledge Generated: Specific details of the system operational objective (A.B).

2. **Instructional Objective:** Interpret the system operational objective in terms of a general function (2.1-B.B).

   Activity: Write the general function that represents the principle concept of the system operational objective in its most basic, first principles, foundational constructs (e.g., in terms of basic physics). Generalizing the operational objective into an implementation independent function helps overcome mental set by abstracting out previous physical design solution assumptions that may be associated with the operational objective.

Knowledge Generated: General system function (B.B).

3. **Instructional Objective:** Provide examples of specific techniques that accomplish the general function (2.2-B.B).

   Activity: Write examples of specific functional techniques that carry out the system function. Choose short, distinct, and comprehensive names for the techniques. The techniques should be implementation-independent.

   Knowledge Generated: Specific system functional techniques (C.B).

4. **Instructional Objective:** Classify the functional techniques (2.3-C.B).

   Activity: Arrange the specific system functional techniques into a categorical hierarchy tree based on common concepts and principles. Group into categories of no more than five techniques. Choose short, distinct, and comprehensive names for categories.

   Knowledge Generated: Functional technique categories (B.A).

Evaluation Criteria Table

Educational Objective—Ability to explain a set of evaluation criteria and their relative importance with respect to the system.

Tool Description—This tool defines a set of criteria for evaluating the system concepts. The table contains the criteria, its definition, examples of systems that do well (satisfactory) and poorly (unsatisfactory) with respect to the criteria, an assigned weight to communicate importance with respect to the system, and rationale for the weight. The satisfactory and unsatisfactory system examples help calibrate the minimum and maximum scores when applying the Evaluation Criteria in the Systems Evaluation Matrices, as well as help make abstract criteria more concrete (assisting with comprehension and retention). Fig. 7 and Tab. 4 show the layout of the Evaluation Criteria Table and associated instructional objectives classified using Bloom's Taxonomy. Tab. 5 provides an example for the Transfer Subsystem.

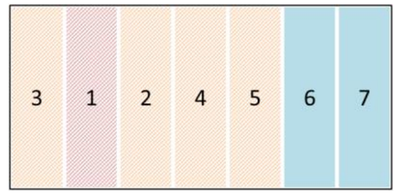


Figure 7. Evaluation Criteria Table layout labeled by step.

Table 4. Evaluation Criteria Table classification of objectives labeled by step.

		Cognitive Process					
	Bloom's Taxonomy Matrix	Remember	Understand	Apply	Analyze	Evaluate	Create
Knowledge	Factual	1	2,3,4,5				
	Conceptual					6,7	

Steps:

1. **Instructional Objective:** Identify the system evaluation criteria (1.1-A.A).

   Activity: List criteria for evaluating the system concepts. Examples include functional requirements, non-functional requirements, standards, institutional engineering design principles, engineering best practices, and considerations for benefits, risks, and success at the project, program, and enterprise levels.

   Knowledge Generated: Evaluation criteria (A.A).

2. **Instructional Objective:** Define the evaluation criteria (2.4-A.B).

   Activity: Define each criteria based on its meaning as it applies to the system.

   Knowledge Generated: Evaluation criteria definitions (A.B).

3. **Instructional Objective:** Categorize the evaluation criteria based on common concepts and principles (2.3-A.B).

Table 5: Example Evaluation Criteria Table (Weights: 0-3 = Not critical, 4-7 = Semi-critical, 8-10 = Critical).

Criteria			Definition	Example of a Satisfactory System	Example of an Unsatisfactory System	Weight	Rationale
Intrinsic Design Criteria	System Resources	Mass	Physical mass of system (CBE + contingency) measured in kg	Hinged link with 1 actuator to close PCV Lid over OS and onto PCV Base has a mass of 5 kg	6 DOF arm for OS manipulation plus 6 DOF Stewart platform for PCV Lid placement has a mass of 50 kg	9	System mass critically affects the mission timeline due to longer acceleration times
		Volume	Stowed volume measured in m^3	Hinged link with 1 actuator to close PCV Lid over OS and onto PCV Base occupies 0.03 m^3	Four bar linkage with PCV Lid and link transfer with cone occupies 0.5 m^3 when stowed	7	Larger stowed volume limits volume availability for supplemental payloads (e.g., sensors, instruments)
	System Parameters	Mechanism Count	Number of independent moving elements within the system	Linear actuator with PCV Lid to assemble OS into PCV Base (1 mechanism)	1 DOF arm to load OS in PCV Base, 1 DOF arm to position PCV Lid over PCV Base, 1 DOF arm to assemble PCV (3 mechanisms)	4	Larger number of mechanisms requires additional engineering support and development program (more resources, but implementable)
		Actuator Count	Number of actuators within the system	Hinged link with 1 actuator to close PCV Lid over OS and onto PCV Base (1 actuator)	6 DOF arm for OS manipulation plus 6 DOF arm for PCV Lid manipulation (12 actuators)	6	Larger number of actuators requires more drivers and avionics support (important, but not driving)
Life Cycle Criteria	Development	Concept Maturity Level	Concept Maturity Level (CML) as defined in [33]	Detailed design of concept developed to level of Critical Design Review criteria (CML 9)	High-level concept sketch without supporting analysis (CML 1)	3	Higher CML reduces risks and development time, but ample development time currently available
		Complexity	C = (N1 x N2 x N3)^(1/3), where N1 = number of elements, N2 = number of types of elements, N3 = number of interfaces [1]	Hinged lid with 1 actuator (N1 = 2, N2 = 2, N3 = 3, C = 2.3)	6 DOF arm for OS manipulation plus 6 DOF Stewart platform for PCV Lid placement (N1 = 24, N2 = 4, N3 = 50, C = 16.9)	4	Higher complexity increases design, assembly, integration, and test challenges (important, but not driving)

Activity: Rearrange the criteria into categories based on common concepts and principles. Group into categories of no more than five criteria. Use several levels of categories if needed, creating new columns to the left of the criteria for each category level. Choose short, distinct, and comprehensive names for categories.

Knowledge Generated: Evaluation criteria categories (B.A).

4. **Instructional Objective:** Provide an example of a satisfactory system for each evaluation criteria (2.2-A.B).

   Activity: Write an example of a system that satisfies each evaluation criteria, along with a short explanation of why. Providing more concrete examples better supports understanding of the criteria.

   Knowledge Generated: System examples that satisfy the criteria (B.A).

5. **Instructional Objective:** Provide an example of an unsatisfactory system for each evaluation criteria (2.2-A.B).

   Activity: Write an example of a system that does not satisfy each evaluation criteria, along with a short explanation of why. Providing more concrete examples better supports understanding of the criteria.

   Knowledge Generated: System examples that do not satisfy the criteria (B.A).

6. **Instructional Objective:** Weight each criteria based on importance to the system relative to other criteria (5.2-B.B).

   Activity: Write a numerical weight for each criteria based on its importance to the system relative to the other criteria. Examples of methods for determining weights are described in [25], [26], and [34]. Individually evaluating the importance of each criteria helps identify any unnecessary constraints (through application of lower weights relative to more important constraints).

Knowledge Generated: Evaluation criteria weights (B.A).

7. **Instructional Objective:** Provide the rationale for each evaluation criteria weight (5.2-B.B).

   Activity: Write the rationale for the weight assignment for each evaluation criteria.

   Knowledge Generated: Evaluation criteria weight rationales (A.B).

Discovered Systems Evaluation Matrix

Educational Objective—Ability to explain existing system concepts and their functional technique, structure, composition, and assessment with respect to the evaluation criteria.

Tool Description—This tool captures knowledge of existing relevant systems, their function, structure, and elements, as well as their assessment relative to the set of evaluation criteria defined in the Evaluation Criteria Table. Blocks 1, 2, and 3 reproduce the evaluation criteria from the Evaluation Criteria Table in the same categorical grouping, along with their weights, so that they can be applied in the Systems Evaluation Matrix. Blocks labelled 0 are optional, but may be useful for understanding the system concepts and elements. Fig. 8 and Tab. 6 show the layout of the Discovered Systems Evaluation Matrix and associated instructional objectives classified using Bloom's Taxonomy. Tab. 7 provides an example for the Transfer Subsystem.

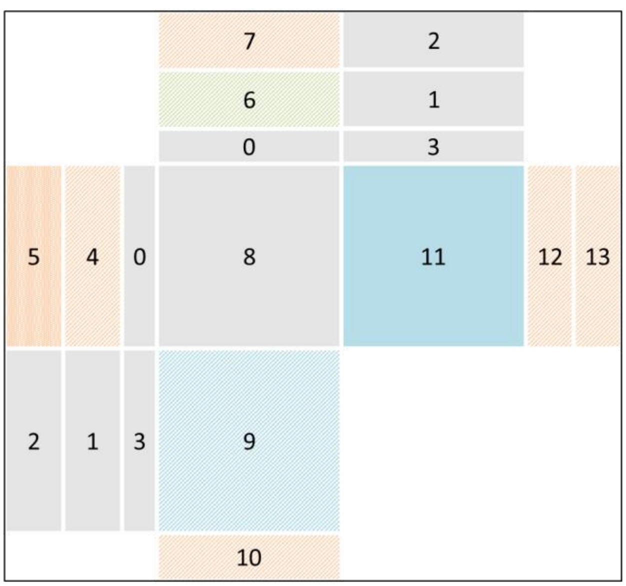


Figure 8. Discovered Systems Evaluation Matrix layout labeled by step.

Table 6. Discovered Systems Evaluation Matrix classification of objectives labeled by step.

		Cognitive Process					
	Bloom's Taxonomy Matrix	Remember	Understand	Apply	Analyze	Evaluate	Create
Knowledge	Factual		4,7,10, 12,13		6	9	
	Conceptual					11	
	Procedural		5				

Steps:

1. List the evaluation criteria from the Evaluation Criteria Table.

2. List the categories for the evaluation criteria from the Evaluation Criteria Table (maintain the same grouping structure for the criteria as in the Evaluation Criteria Table).

3. List the weights for the evaluation criteria from the Evaluation Criteria Table.

4. **Instructional Objective:** Distinguish system concepts that perform the system function from pre-existing system concepts (2.3-A.B).

   Activity: List pre-existing system concepts discovered from background research and literature review that perform the system function. Sources include concepts from previous project efforts, focused technology efforts, state of the art commercial products, state of technology research, and previously developed or implemented systems. The system operational objective, general system function, specific system functional techniques, and functional technique categories from the Function Tree provide initial key words and search categories.

   Knowledge Generated: Relevant pre-existing system concepts (A.B).

5. **Instructional Objective:** Categorize the system concepts based on specific functional technique (2.3-C.B).

   Activity: Rearrange the system concepts into categories based on specific functional techniques. Group into categories of no more than five concepts. Use several levels of categories if needed, creating new columns to the left of the concepts for each category level. Choose short, distinct, and comprehensive names for categories. The categories may correlate with the functional technique categories in the Function Tree.

Table 7: Example Discovered Systems Evaluation Matrix.

Legend	Low	High
Criteria Score	1	5
Normalized Element Score	0.0	1.0
Normalized Concept Structure Score	0.0	1.0
Normalized Total Concept Score	0.0	1.0

System Element			Actuation	Transmission			Linkage		Criteria	System Resources		System Parameters		Development			
			Rotary Motor	Gearing	Belt	Lead Screw	Link End at Joints	Four Bar		Mass	Volume	Mechanism Count	Actuator Count	Concept Maturity Level	Complexity	Normalized Concept Structure Score	Normalized Total Concept Score
System Concept		DOF							Weight	9	7	4	6	3	4		
Link Transfer	Blades	3	3	3			2	1		3	3	3	3	4	2	0.6	0.8
Arm Transfer	3 DOF Turret Arm	3	3	3			2			2	4	5	3	3	3	0.6	0.8
	Gripper Arm	6	6	6			5			1	4	4	1	1	1	0.4	0.7
Paddle Transfer	Dorade	1	1	1			1			5	3	5	5	1	5	0.8	0.9
	Douter	1	1	1	1		1			4	5	4	5	2	4	0.8	0.9
Linear Actuator	Pick-Place Arm	2	2	1		1	1			2	3	3	4	2	3	0.6	0.7
	Crane	2	2	1		1	1			2	3	5	4	1	3	0.6	0.7
Criteria		Weight															
System Resources	Mass	9	5	3	5	1	5	1									
	Volume	7	5	5	4	2	5	3									
System Parameters	Mechanism Count	4	5	5	3	3	5	1									
	Actuator Count	6	5	5	5	5	5	5									
Development	Concept Maturity Level	3	5	5	4	2	5	3									
	Complexity	4	5	5	3	1	5	3									
	Normalized Element Score		1	0.9	0.8	0.5	1	0.5									

Knowledge Generated: System concept functional technique categories (B.A).

6. **Instructional Objective:** Decompose the system concepts into distinct functional elements (4.1-A.B).

   Activity: Distinguish the relevant elements of the system concepts that contribute to the system function. Limit the elements of each system concept to no more than four. This helps keep the number of elements within the limits of visual short-term memory (i.e. a manageable number of chunks that can be manipulated within the VSSP during system analysis and synthesis). Choose short, distinct, and comprehensive names for elements.

   Knowledge Generated: System concept functional elements (A.B).

7. **Instructional Objective:** Categorize the system elements based on function (2.3-A.B).

   Activity: Rearrange the system elements into categories based on general function. Group into categories of no more than five elements. Use several levels of categories if needed, creating new rows above the elements for each category level. Choose short, distinct, and comprehensive names for categories.

   Knowledge Generated: System element functional categories (B.A).

8. Map system elements to system concepts and enter the number of instances of each element that exist within the system.

9. **Instructional Objective:** Score system elements relative to evaluation criteria (5.2-A.B).

   Activity: Write a numerical score for each system functional element relative to each criteria.

   Knowledge Generated: Element evaluation criteria scores (A.B).

10. **Instructional Objective:** Calculate a total evaluation score for system elements (2.4-A.B).

    Activity: Write a total numerical score for each system element that is a function of each element's individual criteria score and the criteria's weight. Examples of methods for calculating total scores are described in [25], [26], and [34].

    Knowledge Generated: Total element evaluation scores (A.B).

11. **Instructional Objective:** Score system concept structures relative to evaluation criteria (5.2-B.C).

    Activity: Write a numerical score for each functional system concept relative to each criteria. The objective is to evaluate the system concepts based on their system concept structures, the functional technique that arises from the structures, and other emergent system properties that arise from its particular composition of functional elements, as opposed to the internal attributes of the functional elements themselves (the functional elements were evaluated separately in Step 9 and will be combined with the system concept structure evaluation scores in Step 13).

    Knowledge Generated: System concept structure evaluation criteria scores (A.B).

12. **Instructional Objective:** Calculate a total evaluation score for system concept structures (2.4-A.B).

    Activity: Write a total numerical score for each system concept structure that is a function of each concept structure's individual criteria score and the criteria's weight. Examples of methods for calculating total scores are described in [25], [26], and [34].

    Knowledge Generated: Total system concept structure evaluation scores (A.B).

13. **Instructional Objective:** Calculate a total evaluation score for system concepts (2.4-A.B).

    Activity: Write a total numerical score for each system concept that is a function of both the concept's structure and its elements' scores. Determining the mathematical method to calculate the total score may require critiquing the level of importance (or weight) each element plays in the final system concept relative to one another, as well as to the system concept structure.

    Knowledge Generated: Total system concept evaluation scores (A.B).

0. Provide any additional information related to the system concepts or elements that may help with their comprehension. These blocks are optional.

Synthesized Systems Evaluation Matrix

Educational Objective—Ability to explain new system concepts and their functional technique, structure, composition, and assessment with respect to the evaluation criteria.

Tool Description—This tool captures knowledge of newly generated systems, their function, structure, and components, as well as their assessment relative to the set of evaluation criteria defined in the Evaluation Criteria Table. It follows the same format as the Discovered Systems Evaluation Matrix, with the only difference being that the system concepts are synthesized, not discovered. Fig. 9 and Tab. 8 show the layout of the Synthesized Systems Evaluation Matrix and associated instructional objectives classified using Bloom's Taxonomy.

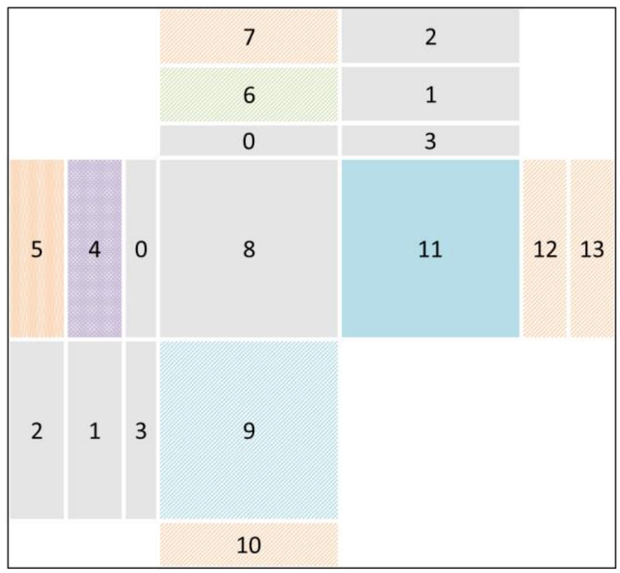


Figure 9. Synthesized Systems Evaluation Matrix layout labeled by step.

Table 8. Synthesized Systems Evaluation Matrix classification of objectives labeled by step.

		Cognitive Process					
	Bloom's Taxonomy Matrix	Remember	Understand	Apply	Analyze	Evaluate	Create
Knowledge	Factual		7,10,12, 13		6	9	
	Conceptual					11	
	Procedural		5				4

Steps:

1-3. Same as Discovered Systems Evaluation Matrix.

4. **Instructional Objective:** Generate new system concepts (6.1-C.B).

   Activity: Generate new system concepts using knowledge from pre-existing system concept techniques through recombination of existing elements using existing system concept structures (evolutionary), combining elements into new structures (revolutionary), or performing the aforementioned with newly identified or generated elements. Choose short, distinct, and comprehensive names for the new system concepts.

   Knowledge Generated: New system concepts (C.B).

5-13. Same as Discovered Systems Evaluation Matrix.

0. Same as Discovered Systems Evaluation Matrix.

System Concepts Visual-Verbal Document

Educational Objective—Ability to visually and verbally describe system concepts and system elements from various domains.

Tool Description—This tool visually and verbally captures system concepts within various domains. Categorizing system concepts within their originating domains provides initial search paths and targets specific information sources (e.g., within scientific literature, internet websites, catalogs, or project archives) to discover concepts, as well as provide perceptual, semantic, and conceptual cognitive priming to stimulate recall of potentially relevant system concepts stored in declarative long-term memory. For each concept, both visual and verbal representations are compiled in close proximity to one another to support deeper understanding of the concept through the principle of spatial contiguity [32]. New domains may be identified during the search process, during which they can be added to Block 1. Fig. 10 and Tab. 9 show the layout of the System Concepts Visual-Verbal Document and associated instructional objectives classified using Bloom's Taxonomy. Fig. 11 provides an example for the Transfer Subsystem.

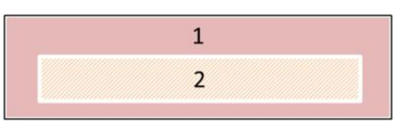


Figure 10. System Concepts Visual-Verbal Document layout labeled by step.

Table 9. System Concepts Visual-Verbal Document classification of objectives labeled by step.

		Cognitive Process					
	Bloom's Taxonomy Matrix	Remember	Understand	Apply	Analyze	Evaluate	Create
Knowledge	Factual		2				
	Conceptual	1					

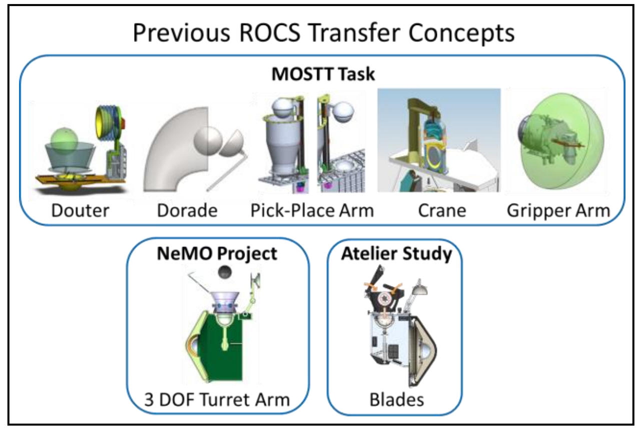


Figure 11. Example System Concepts Visual-Verbal Document.

Steps:

1. **Instructional Objective:** Recall system concept domains (1.2-B.A).

   Activity: Write domains that may provide sources for system concepts (e.g., industries, technical fields, research topics, focused technology tasks).

   Knowledge Generated: System concept domains (B.A).

2. **Instructional Objective:** Distinguish system concepts that perform the system function from pre-existing system concepts within the various source domains (2.3-A.B).

   Activity: Identify examples of relevant system concepts through both internal (long-term memory) and external searches (physical databases) within the source domains. Aim for a variety of resources (e.g., scientific literature, internet sources, catalogs, project archives, subject matter experts) and search methods (e.g., long-term memory recall, internet search engines, personal discussions, librarian research requests) with the goal of gathering a representative sampling of the population of existing concept types across domains. Use the domains in Step 1 as initial search paths. Use the system operational objective, general system function, specific system functional techniques, and functional technique categories from the Function Tree as key words and search categories. Record both a visual representation (e.g., picture, rendering, sketch, or diagram) and verbal representation (descriptive name). Choose short, distinct, and comprehensive names for system concepts. Place the name directly under the visual.

Knowledge Generated: Relevant pre-existing system concepts (A.B).

System Elements Visual-Verbal Document

Educational Objective—Ability to visually and verbally describe system elements from the system element functional categories.

Tool Description—This tool visually and verbally captures the system elements within the system element functional categories from all System Evaluation Matrices. For each element, both visual and verbal representations are compiled in close proximity to one another to support deeper understanding of the element through the principle of spatial contiguity [32]. Fig. 12 and Tab. 10 show the layout of the System Elements Visual-Verbal Document and associated instructional objectives classified using Bloom's Taxonomy. Fig. 13 provides an example for the Transfer Subsystem.

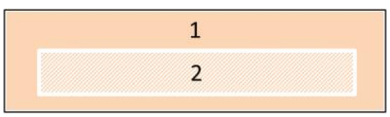


Figure 12. System Elements Visual-Verbal Document layout labeled by step.

Table 10. System Elements Visual-Verbal Document classification of objectives labeled by step.

		Cognitive Process					
	Bloom's Taxonomy Matrix	Remember	Understand	Apply	Analyze	Evaluate	Create
Knowledge	Factual		2				
	Conceptual		1				

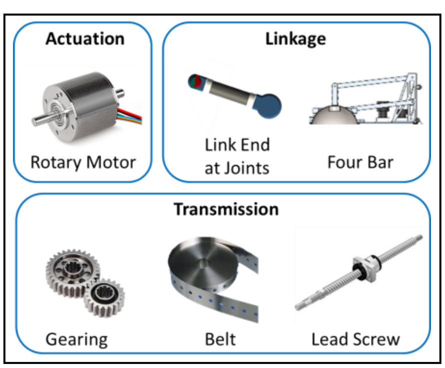


Figure 13. Example System Elements Visual-Verbal Document.

Steps:

1. **Instructional Objective:** Consolidate system element functional categories (2.3-B.A).

   Activity: Write system element functional categories from all System Evaluation Matrices. Combine or subsume functional categories that perform identical functions.

   Knowledge Generated: Consolidated system element functional categories (B.A).

2. **Instructional Objective:** Categorize system elements within the consolidated system element functional categories (2.3-A.B).

   Activity: Categorize distinct system elements from all System Evaluation Matrices within the consolidated system element functional categories. Choose the most descriptive and comprehensive visual and verbal representations for system elements where several instances exist from which to choose.

   Knowledge Generated: Distinct system elements (A.B).

Compatibility Matrix

Educational Objective—Ability to explain the compatibility of each system element relative to both itself and others within the system.

Tool Description—This tool captures the compatibility of each system element relative to both itself and other system elements. Two-element interactions are assessed based on their potential effects on the element functions, as well as their potential effects on element evaluation criteria scores. Blocks 1 and 2 reproduce the system elements from the System Elements Visual-Verbal Document organized within the same consolidated system element functional categories. Note that the entries in Block 3 will be symmetric about the diagonal. Filling out the entire table facilitates calculating a total compatibility score from the entries along the entire row of the element, which is entered into Block 4. The Compatibility Matrix provides a means to methodically bound the combination option space amongst system elements by revealing poor combinations, as well as beneficial combinations that could lead to potentially good system designs. Additionally, the activity forces remote associations, which may potentially develop new emergent system behaviors, and may combat problem solving blocks (e.g., functional fixedness). Fig. 14 and Tab. 11 show the layout of the Compatibility Matrix and associated instructional objectives classified using Bloom's Taxonomy. Tab. 12 provides an example for the Transfer Subsystem.

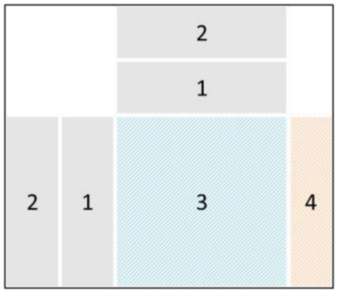


Figure 14. Compatibility Matrix layout labeled by step.

Table 11. Compatibility Matrix classification of objectives labeled by step.

		Cognitive Process					
	Bloom's Taxonomy Matrix	Remember	Understand	Apply	Analyze	Evaluate	Create
Knowledge	Factual		4			3	
	Conceptual						

Table 12. Example Compatibility Matrix.

Legend/Score	
Positive Synergy	5
N/A	4
Independent	3
Indeterminable	3
Negative Synergy	2
Not Compatible	1

		Actuation	Transmission			Linkage		
System Element		Rotary Motor	Gearing	Belt	Lead Screw	Link End at Joints	Four Bar	Normalized Sum
Actuation	Rotary Motor	5	5	5	5	5	5	1
Transmission	Gearing	5	5	3	3	3	3	0.7
	Belt	5	3	5	3	3	3	0.7
	Lead Screw	5	3	3	5	4	3	0.8
Linkage	Link End at Joints	5	3	3	4	5	4	0.8
	Four Bar	5	3	3	3	4	5	0.8

Steps:

1. List the distinct system elements from the System Elements Visual-Verbal Document.

2. List the consolidated system element functional categories from the System Elements Visual-Verbal Document.

3. **Instructional Objective:** Score compatibility of each system element with itself and others (5.2-A.B).

   Activity: For each system element row and column combination, assess the compatibility between the two components and select a score. Assess compatibility based on how the two elements may cooperate functionally, fit together structurally, and interact with one another either synergistically or non-synergistically relative to their impact on the evaluation criteria. An example of categories of compatibility from worst (awarded the lowest score) to best (awarded the highest score): "Not Compatible" (both could never exist together), "Negative Synergy" (one would hurt the functionality or evaluation scores of the other), "Indeterminable" (unknown compatibility), "Independent" (no expected effects), "N/A" (not applicable because both components would not be needed together), and "Positive Synergy" (components complement one another, leading to improved functionality or evaluation scores).

   Knowledge Generated: System element compatibility scores (A.B).

4. **Instructional Objective:** Calculate a total compatibility score for system elements (2.4-A.B).

   Activity: Write a total numerical score for each system element that is a function of each element's individual compatibility scores. Higher compatibility scores highlight elements most compatible with other system elements and help focus attention on those elements when synthesizing new system concepts, which may provide higher probabilities of leading to more successful, flexible, modular, and resourceful concepts.

   Knowledge Generated: Total system element compatibility scores (A.B).

Recommended Concepts Table

Educational Objective—Ability to create an argument for the purpose of informing, persuading, and eliciting stakeholder acceptance of a prioritized system concept amongst a selective set of recommended system concepts.

Tool Description—This tool delivers a prioritized list of the recommended system concepts based on a qualitative assessment of all knowledge generated on the system. The list is supplemented by a selective set of determinant criteria that are considered both important to the stakeholders for decision making (or should be convinced of the importance if currently not considered by the stakeholders) and clearly distinguish the system concepts from one another. The number of recommended system concepts and determinant criteria are both limited to five. The Recommended Concepts Table provides a means to select system concepts both through quantitative methods (e.g., total system concept scores calculated in the Evaluation Matrices) and qualitative methods (e.g., system concepts that show good compatibility with other systems or stakeholder preferences), base those recommendations on the most important criteria that highlight the differences between the concepts, and allow for effective debate in a design review without overloading the review board with information (through limiting the concepts and criteria to a manageable number that can be stored and processed in working memory). Fig. 15 and Tab. 13 show the layout of the Recommended Concepts Table and associated instructional objectives classified using Bloom's Taxonomy. Tab. 14 provides an example for the Transfer Subsystem.

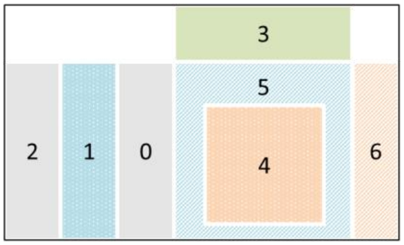


Figure 15. Recommended Concepts Table layout labeled by step.

Table 13. Recommended Concepts Table classification of objectives labeled by step.

		Cognitive Process					
	Bloom's Taxonomy Matrix	Remember	Understand	Apply	Analyze	Evaluate	Create
Knowledge	Factual		6			5	
	Conceptual				3		
	Procedural		4			1	

Steps:

1. **Instructional Objective:** Select recommended system concepts (5.2-C.B).

   Activity: List a set of recommended system concepts selected based on all knowledge generated on the system. Recommended system concepts may be the overall top scoring system concepts out of the Systems Evaluation Matrices, as well as any system concepts that are the current status quo or preferred by the stakeholders. Additionally, if the system is an element of a larger system, a system concept that scores high in compatibility with other systems that potentially interact with it may be another recommended system concept. Limit the number of recommended system concepts to five.

   Knowledge Generated: Recommended system concepts (A.B).

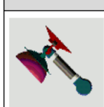
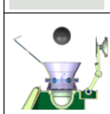
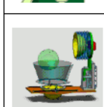
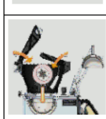
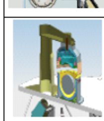
2. Add the visual from the System Concepts Visual-Verbal Document for each of the recommended system concepts.

3. **Instructional Objective:** Select determinant criteria relevant to the recommended system concepts (4.1-B.B).

   Activity: List a set of criteria that are both high in importance to the system and its stakeholders (e.g., criteria from the Evaluation Criteria Matrix with high weights) and differentiate the recommended system concepts from one another (e.g., criteria where the recommended concepts varied greatly in scores). Limit the number of determinant criteria to five.

   Knowledge Generated: Determinant criteria for recommended system concepts (A.B).

Table 14: Example Recommended Concepts Table (Red = Poor, Yellow = Medium, Green = Good).

Transfer		Mass	BTC Hardware Protection	Complexity	Actuator Count	Compatibility w/BTC	Rank
	**2 DOF Turret Arm**	17 kg	PCV hardware protected from energetic OS	Complexity, C = 5.1	2 actuators	Provides curved motion during PCV assembly	**1**
	**3 DOF Turret Arm**	23 kg	PCV hardware protected from energetic OS	Complexity, C = 7.1	3 actuators	Provides full linear motion during PCV assembly	**2**
	**Douter**	15 kg	PCV Lid and Base contact energetic OS	Complexity, C = 5.1	1 actuator	Provides full linear motion during PCV assembly	**3**
	**Blades**	22 kg	PCV Base contacts energetic OS	Complexity, C = 7.1	3 actuators	Provides limited linear motion during PCV assembly	**4**
	**Crane**	25 kg	PCV Lid and Base contact energetic OS	Complexity, C = 4.9	2 actuators	Provides full linear motion during PCV assembly	**5**

4. **Instructional Objective:** Summarize system concept attributes for each determinant criteria that differentiate the concepts (2.4-C.B).

   Activity: Summarize system concept attributes for each determinant criteria that differentiate the concepts from one another.

   Knowledge Generated: Differentiating system concept attributes for determinant criteria (A.B).

5. **Instructional Objective:** Rate system concepts on the determinant criteria relative to one another (5.2-A.B).

   Activity: Qualitatively rate each system concept on the determinant criteria, calibrating the ratings to cover the full scale over the recommended system concepts.

   Knowledge Generated: System concept determinant criteria ratings (A.B).

6. **Instructional Objective:** Rank the recommended system concepts (2.5-A.B).

   Activity: Rank the recommended system concepts based on their ratings in Block 5. Order the system concepts within the table to place the highest ranked concept on the top and lowest ranked concept on the bottom.

   Knowledge Generated: Prioritized list of recommended system concepts (B.C).

0. Provide any additional information related to the recommended system concepts that may help with their comprehension (e.g., system elements). This block is optional.

5. Systems Architecting Methodology

The architecting methodology process is shown in Fig. 16 and consists of nine steps. The steps in the process correlate to stages in the creativity process, are each represented by a tool instance, and are sequentially numbered by order of operation. Steps 1 and 2 relate to the Formulate Problem stage and contribute to better understanding of the engineering problem the system must solve, as well as the criteria that judges the acceptability of the system solution.

Steps 3, 4, and 5 facilitate the creation and discovery of an initial set of system concepts and ideas for the creative Process to work with. Brainstorming activities associated with Step 3 provide a mechanism to collect relevant concepts stored in long-term memory or generated through early initial concept synthesis, as well as provide a means to avoid mental set that may limit divergent thinking later on in the process. An appropriate goal for brainstorming is to collect ideas from a diverse set of individuals (e.g., domain experts, customers, users, project team members, academia, etc.) to gather a large quantity of ideas, as well as diverse categories of ideas. Research activities associated with Step 4 capture knowledge relevant to the Product and ensure that prior development efforts and associated technology investments are acknowledged. Research activities associated with Step 5 gather ideas related to the Product function (but for different problems) to expand the solution option space and trigger out of the box thinking, potentially leading to more unconventional and revolutionary concepts.

Step 6 provides a means to understand the system elements and their compatibilities within the system context, as well as initiate remote associations that may promote the generation of new system compositions. Step 7 is the creative ideation stage where new system concepts are synthesized. Rest periods between concept generation sessions were incorporated to provide time for incubation, which help the individual recover from mental fatigue, beak fixation on particular solutions, allow time for spreading activation, and provide chances for opportunistic assimilation of new ideas that may be beneficial to the problem solving process [9]. Step 8 is the down-select stage where preferred system concepts are recommended, taking into consideration both previously identified concepts from Steps 3, 4, and 5, as well as newly created concepts from Step 7. Step 9 consists of prototyping recommended concepts from Step 8.

For all the instantiated evaluation matrices, an associated Visual-Verbal Document is created concurrently to document the system concepts of each matrix. Additionally, a Visual-Verbal Document consisting of the functional elements is created concurrently with the evaluation matrices in Steps 3, 4, and 5 to visually and verbally document the system functional elements identified during system concept functional decompositions. This document should be completed prior to moving on to Step 6, as having a visual and verbal representation of the elements can assist with assessing their compatibilities. The Prototype activity in Step 9 is similar to the Visual-Verbal Document, in that it provides a means to physically and concretely represent the system concepts and elements. As with the other tools, deeper knowledge of the system concepts is generated through prototyping, which implements the Bloom's Taxonomy cognitive process levels of Generation (6.1), Planning (6.2), and Producing (6.3).

Step 3, 4, 5, and 6 carry the bulk of the learning activities that capture and generate the factual, conceptual, and procedural knowledge used for the creation of new system concepts, and, therefore, are packaged in a "System Knowledge Generation" box. The whole process is packaged in a "System Synthesis" box, as the purpose of these activities is to support new system synthesis.

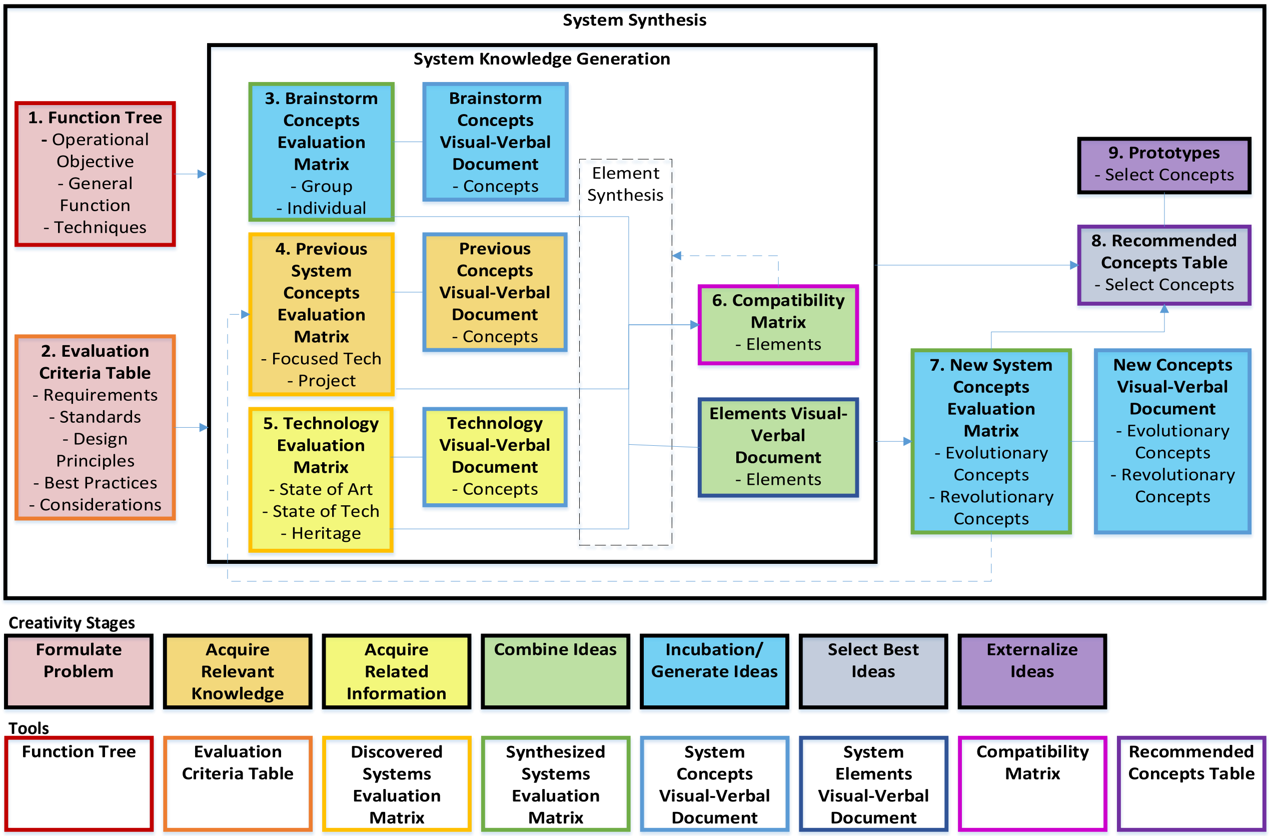


Figure 16: Systems synthesis process used in the architecting methodology.

Steps 8 and 9 together help to further define the creative Product along an axis of abstraction from a more conceptual to a more physical form. The Recommended Concepts Table and prototypes produced in Steps 8 and 9 aid with knowledge generation and can assist with Process, Promotion, and Proof activities. Product prototype attributes particularly useful to the Process and Proof activities include verifiability (a feedback flow between the Product and Person) and validatability (a feedback flow between the Product and Press). Verifiability and validatability (V&V) can be improved through developing prototypes with an open architecture. Open architectures help the individual (i.e. learner) access the underlying knowledge associated with the product design that may be needed to cognitively process (i.e., remember, understand, apply, analyze, evaluate, and create) for effective V&V activities. For example, the cognitive processes in the remember category are associated with verification by inspection, the apply category with verification by test/demonstration, and the analysis category with verification by analysis. Additionally, developing prototypes that highlight the determinant criteria can be useful for Promotion and Proof activities by focusing limited resources and attention on the criteria deemed most critical to Product success and in distinguishing it amongst its alternatives.

A dashed box within the System Knowledge Generation box labelled "Element Synthesis" provides a means to apply the System Synthesis process recursively at the element level, and iteratively for multiple elements. This allows for the creation of new element options for compatibility assessment and new system synthesis. A general example of System Synthesis with three system elements is shown in Fig. 17. A specific implementation of System Synthesis with three system elements for the ROCS Capture and Orient Module is shown in Fig. 18.

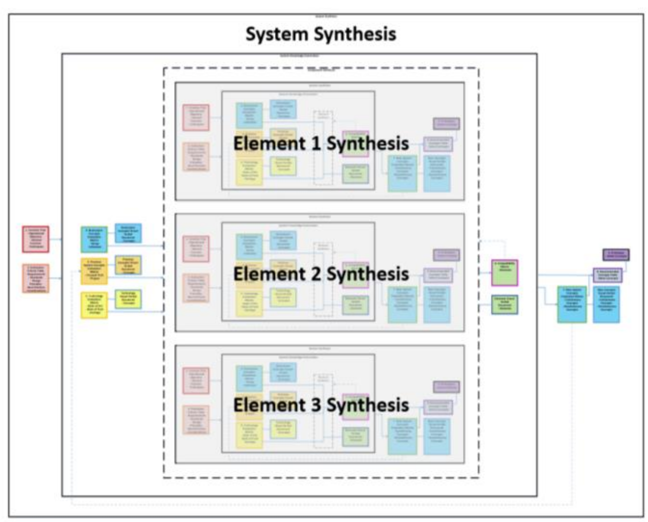


Figure 17. System synthesis process with element synthesis.

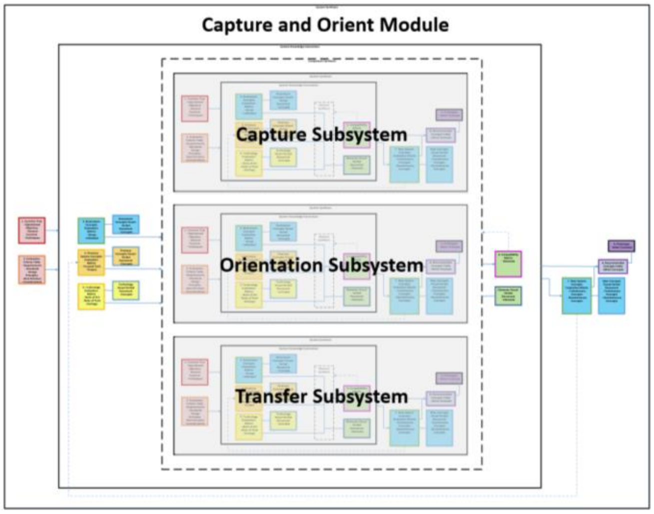


Figure 18. Example system synthesis process with element synthesis for the Capture and Orient Module.

Two feedback loops are indicated by dotted flow lines. The flow line from Step 7 to Step 4 allows for newly generated system concepts to be migrated to the Previous System Concepts Evaluation Matrix in the case where another iteration of Steps 4, 6, and 7 is desired. The flow line from Step 6 to the Element Synthesis box allows element compatibility knowledge generated to flow back to the element synthesis processes to be potentially assessed as additional determinant criteria for element-level Recommended Concepts Tables. This ensures that system elements are not simply recommended based on evaluation at the element level, but take into account how they interact with other elements at the higher system level.

6. CASE STUDY

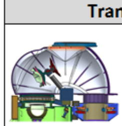
The systems architecting methodology was applied on an orbiting sample capture and orientation system architecture to enable spacecraft-based, on-orbit capture, orientation, and transfer of a Mars sample container into a containment vessel as part of a potential Mars Sample Return (MSR) campaign. The problem definition, evaluation criteria, system concepts investigated, and final system recommendations are described in [8]. The overall Recommended Concepts System for the Capture and Orient Module architecture is shown in Tab. 15.

7. FUTURE WORK

The systems architecting methodology is currently in use on the ROCS Capture and Orient Module described in [8] at the system and subsystem levels. Recommendations on how to refine the methodology will be made based on feedback from the engineering team. Collaboration is in works with systems engineering, cognitive psychology, educational psychology, creativity, and education researchers and practitioners to further develop aspects of the methodology, as well as implement a means to assess its effectiveness.

Future developments includes further integrating into the methodology metacognitive knowledge elements (e.g., strategies and tools for idea generation, techniques to break through creative blocks and cognitive biases, and personal beliefs), affective domain elements (e.g., motivation, feelings, mood, and mindset), and methods developed from marketing and consumer behavior fields addressing Promotion and other interactions with the Press.

Table 15: Recommended Concepts Table for ROCS Capture and Orient Architectures (Red = Poor, Yellow = Medium, Green = Good).

Capture, Orientation, and Transfer		Capture	Orientation	Transfer	Dust Encapsulation	1 G Testable	Impact on OS	BTC Hardware Protection	Deterministic	Rank
	MACARONE	Door	Motorized Cups	2 DOF Turret Arm	Encapsulates dust, enables "Close before contact"	Testable in 1 G	Restricts OS maximum negative feature size	PCV hardware protected from energetic OS	Motorized Cups relies on sensors to be deterministic	1
	Inline Transfer	Door	Motorized Cups	3 DOF Turret Arm	Does not encapsulate dust	Testable in 1 G	Restricts OS maximum negative feature size	PCV hardware protected from energetic OS	Motorized Cups relies on sensors to be deterministic	2
	MOSTT Concept 3	Paddle	Wiper Mechanism	Douter	Does not encapsulate dust	Wiper requires additional features to test in 1 G	Requires positive feature with low friction on OS	PCV Lid and Base contact energetic OS	Wiper deterministically orients OS	3
	Car Wash	Bladed Capture Cone	Wheel Friction Drive	Blades	Does not encapsulate dust	Testable in 1 G	Requires smooth rolling surface on OS	PCV Base contacts energetic OS	Wheel Friction Drive not deterministic	4
	Minimal	Flux Pinning	Flux Pinning	1 DOF Arm	Does not encapsulate dust, minimizes dust generation	Not testable in 1 G	Requires permanent magnets and shielding on OS	OS may impact PCV Base during capture	Flux Pinning deterministically orients OS	5

8. SUMMARY

A systems architecting methodology implemented through cognitive psychological creative processes using Bloom's taxonomy as a framework to generate knowledge required to effectively and systematically synthesize new systems was developed. A summary of the methodology integrating knowledge, evaluation criteria, cognitive processing, and creative synthesis to generate new system concepts is shown in Fig. 19.

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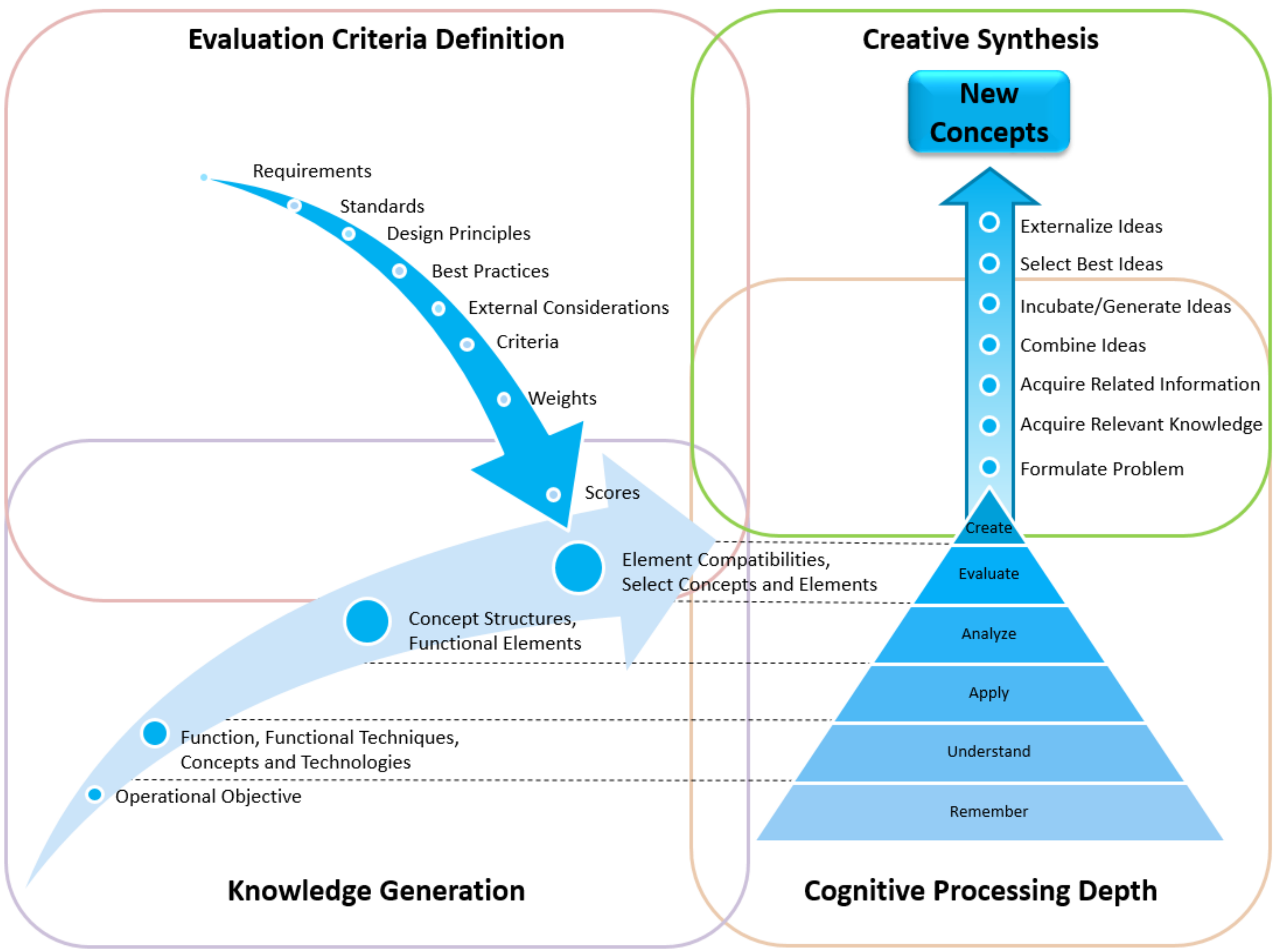

Figure 19. Integrating knowledge, evaluation criteria, cognitive processing, and creative synthesis to generate new system concepts.

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