AC 2009-675: CREATING LEGO PROTOTYPES FOR K-5 USING FUNCTIONAL MODELING

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Creating LEGO Prototypes for K-5 Using Functional Modeling.

Abstract

With design challenges, often K-5 students imagine concepts to create, but find themselves unable to translate their ideas into prototypes. Teachers, especially K-5 teachers, often need assistance with prototyping for design challenges. This research addresses this student and teacher dilemma by providing a web-based tool that combines functional modeling with LEGOs construction. The tool is based on the extensive research in the engineering design methodology community to develop functional modeling to assist engineers in concept generation. The Functional Common Basis (FCB) is a common language that allows functional models created by different individuals to be directly compared and analyzed. In this study, the principles of the FCB are adapted to assist students and teachers in building prototypes with LEGOs. A limited set of functions for designing with LEGO Technics, called the LEGO Functional Common Basis, was developed. The "Design with LEGO" web tool is based on the LEGO Functional Common Basis. The tool has been evaluated during teacher professional development institutes (PDI) that provide hands-on introduction to engineering design. Survey analysis of the tool indicates that teachers exposed to the tool plan on using it in the future. This paper provides an overview of the research on functional modeling with LEGOs, how functional modeling for LEGOs was used as the basis for the web-based tool, and a discussion of the findings that indicate positive results when the tool is used to assist with building LEGO devices as a part of K-5 design challenges.

1.0 Introduction

The National Academies along with many other experts agree that the USA needs to produce more engineers and scientists[1]. Attracting more students to engineering requires improvements to pre-engineering education need. One program that has worked to improve Science, Technology, Engineering and Mathematics (STEM) education is Design Technology and Engineering for America's Children (DTEACh), offered by The University of Texas at Austin. The DTEACh program, which is the focus of this paper, has worked for the last fifteen years to improve the way kindergarten through twelfth grade (K-12) math, science and engineering are taught. The program uses active learning with open-ended design projects to improve students' understanding of math, science and engineering concepts. This research focuses on assisting students with generating prototypes during open-ended design projects. The research has its roots in engineering design theory and methodology research.

2.0 DTEACh Program

For over fifteen years, the DTEACh training institutes have instructed K-5 teachers in STEM concepts with active learning techniques[2,3]. The DTEACh program demonstrates to teachers how the engineering design problem-solving process engages students in learning mathematics and science concepts. DTEACh is offered through the Cockrell School of Engineering at The University of Texas at Austin (http://www.engr.utexas.edu/dteach). The program provides guidance to K-5 teachers on how to use open-ended problems in their classrooms. The institutes include one week of instruction in engineering concepts through the use of everyday technology, directed laboratory activities, and design briefs. The institutes are designed to model the teaching methods the participants will use in their classrooms. Previous assessment has focused on the immediate and long term effectiveness of the institutes using surveys and focus groups[4,5]. This study focuses on how the prototyping process with LEGO Mindstorms in open-ended design projects can be improved.

Focus groups consisting of DTEACh practioners have indicated that transforming design concepts into LEGO hardware is difficult for teachers and is a barrier to classroom adoption of DTEACh. Teachers asked for more tools and concrete examples of design concepts. This problem is not that different from one faced by practicing engineers in industry, where a major challenge is the conversion of concepts from the idea board to working prototypes. Due to this need, research in engineering design methods has been ongoing for many years[6,7]. To address this need for teachers, a tool was created to allow the designer to determine what the design should "do", or how it should function, and then assist the user with examples of the functions implemented in LEGO Technics. The development of the "Design with Lego Tool" was based on research in engineering design, specifically functional modeling.

3.0 Guiding Theory - Functional Modeling

Functional modeling provides a means for decomposing a product's overall function into a set of small, easier-to-solve sub-functions[8]. The proper combination of the sub-functions represents the complete functionality of the product. Many functional modeling approaches specify the use of active verb-object descriptions to generalize a product's function. For example, the well-known Pahl and Beitz approach combines active verb-object descriptions with a graphical method for representing designs functionally[10]. The Pahl and Beitz representation, called a function structure, models a product's functions as boxed verb phrases describing the functions. Arrows are used to represent the flows of energy, materials, and signals connecting the functions. Figure 1 shows an example function structure of the Black and Decker AutoClamp.

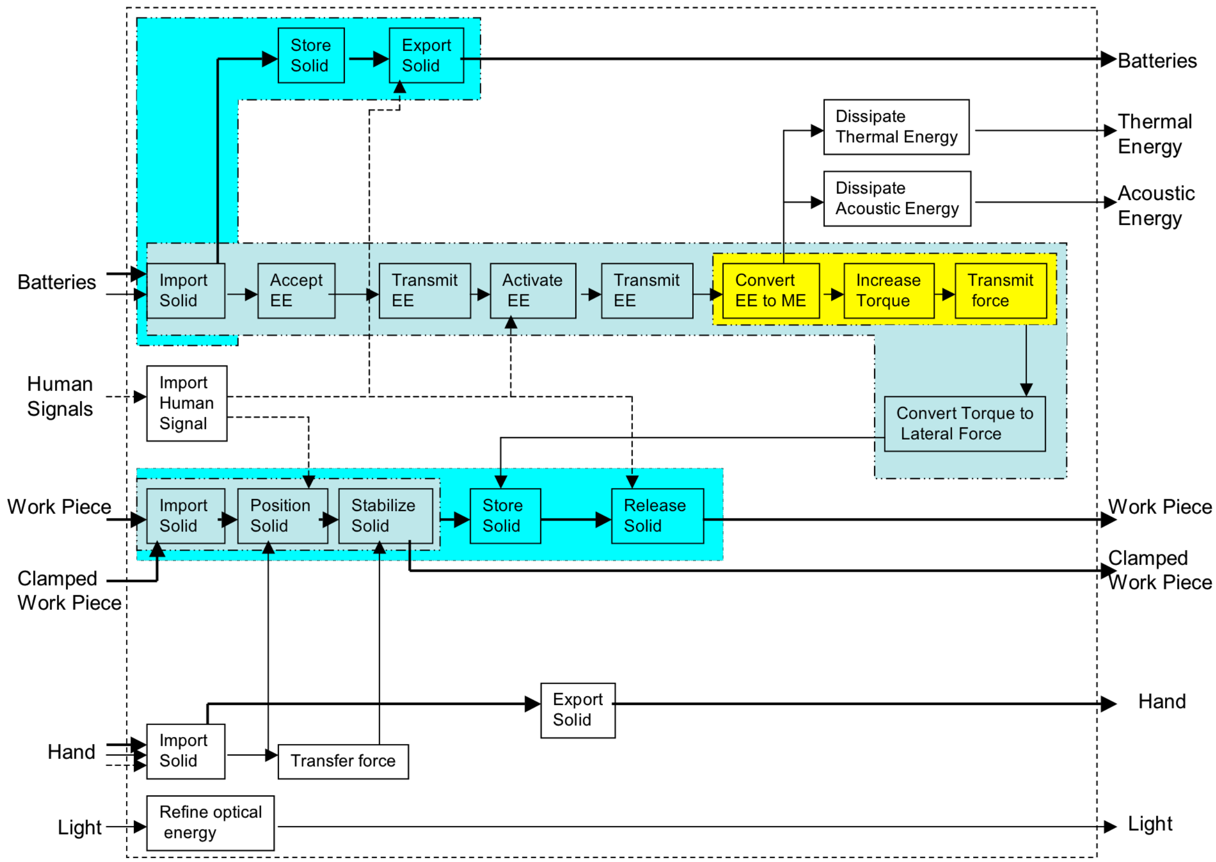

Figure 1: Black and Decker AutoClamp Function Structure

In an effort to create a standardized common language of functional modeling, the National Institute of Standards and Technology (NIST) produced a technical note based on analyzing functional modeling research[15]. As a part of this work, Stone and Wood[15] used their Functional Base Set, a refined set of functions and flows, to establish the Functional Common Basis. The Functional Common Basis established a common language that allows functional models created by different individuals to be directly compared and analyzed. The Functional Common Basis was created by an extensive review of past efforts to establish function and flow terminology and is founded on an empirical study of functional analysis of over a hundred products[8]. This set of generally valid functions provides a high level set of functions that Ford Motor Company, NIST, and many others have used in functional modeling research[15]. The functions of the products were mapped to the function representation to verify that the language of the basis was complete. The Functional Common Basis is shown in Table 1.

Table 1: Functional Common Basis[16]

Class	Basic	Flow class restricted	Synonyms
Channel	Import		Input, Receive, *Allow*, Form entrance, *Capture*
	Export		Discharge, Eject, Dispose, Remove
	Transfer	Transport (M)	Lift, Move
		Transmit (E)	Conduct, Convey
	Guide	Translate	Direct, Straighten, Steer
		Rotate	Turn, Spin
		Allow DOF	Constrain, Unlock
Support	Stop		Insulate, Protect, *Prevent*, Shield, Inhibit
	Stabilize		Steady
	Secure		*Attach*, Mount, Lock, Fasten, Hold
	Position		Orient, Align, Locate
Connect	Couple		Join, Assemble, *Attach*
	Mix		Combine, Blend, Add, Pack, Coalesce
Branch	Separate		Switch, Divide, Release, Detach, Disconnect, Disassemble, Subtract, Valve
		Remove (M)	Cut, Polish, Sand, Drill, Lathe
	Refine		Purify, Strain, Filter, Percolate, Clear
	Distribute		Diverge, Scatter, Disperse, *Diffuse*, Empty
	Dissipate		Absorb, Dampen, Dispel, *Diffuse*, Resist
Provision	Store		Contain, Collect, Reserve, *Capture*
	Supply		Fill, Provide, Replenish, Expose
	Extract		
Control magnitude	Actuate		Start, Initiate
	Regulate		Control, *Allow*, *Prevent*, Enable/Disable, Limit, Interrupt
	Change		Increase, Decrease, Amplify, Reduce, Magnify, Normalize, Multiply, Scale, Rectify, Adjust
	Form		Compact, Crush, Shape, Compress, Pierce
Convert	Convert		Transform, Liquefy, Solidify, Evaporate, Condense, Integrate, Differentiate, Process
Signal	Sense		Perceive, Recognize, Discern, Check, Locate
	Indicate		Mark
	Display		Show
	Measure		Calculate

4.0 Design with LEGO Tool

To create the Design with LEGO Tool, methods for developing previous functional modeling tools were analyzed. In particular, the Functional Common Basis was developed by analysis of products and patents in the selected domain. The resulting functions were categorized to create a set of core functions. The Design with LEGO Tool is based on functional modeling, but is refined to work exclusively with LEGOs and is meant to be simple to understand so that K-5 teachers and students can use it. In developing the Design with LEGO Tool, LEGO designs created for the DTEACh program were functionally analyzed. Eleven LEGO Mindstorms NXT designs from the DTEACh 2007 program were used in this analysis.

4.1 Design with LEGO Tool – Functions

The major functions of all eleven LEGO Designs were mapped to basic functions of the Functional Common Basis. For simplicity of the design tool, the mapping focused on functions that represented a predominant feature of the design of the device. Making the tool as simple as possible to use was a major requirement so that teachers and students feel comfortable using the tool. The building instructions for the devices were analyzed to determine the major functions of the devices. The mapping of the eleven devices' functions to the basic functions in the Functional Common Basis can be seen in Table 2, a modified morphological matrix.

Table 2: LEGO devices mapped to the Functional Common Basis

Devices	Functions																	
	Channel				Support			Connect	Branch	Provision		Control		Convert	Signal			
	Import	Export	Transfer	Guide	Stabilize	Secure	Position	Couple	Distribute	Store	Supply	Actuate	Change	Convert	Sense	Indicate	Display	Measure
All Wheel Vehicle	Sturdy Frame for Hand		Rotational to Linear, Wheel, Gears	Steer Dual	Basic Structure, Pin	Pin	Software, Sensors, Feeler Touch	Pin		Batteries	NXT Electrical	Motor	Rotational to Linear, Wheel, Gears	Rotational to Linear, Wheel, Gears	Light, Sound, Distance, Touch			Light, Sound, Distance, Touch
Automated Door With Sensors	Sturdy Frame for Hand		Rotational to Linear, Tracks, Gears	Track	Basic Structure, Pin, Brick	Pin, Brick	Software, Sensors	Pin, Brick		Batteries	NXT Electrical	Motor	Rotational to Linear, Track, Gears	Rotational to Linear, Tracks, Gears	Light, Sound, Distance, Touch, Rotation, Time	Sound		Light, Sound, Distance, Touch, Rotation, Time
Dispenser	Sturdy Frame for Hand	Conveyer Belt	Rotational to Linear, Tracks, Gears	Track	Basic Structure, Pin, Brick	Pin, Brick	Software, Sensors	Pin, Brick	Conveyer Belt	Batteries	NXT Electrical	Motor	Rotational to Linear, Track, Gears	Rotational to Linear, Tracks, Gears	Light, Rotation			Light, Rotation
Elevator Lift	Sturdy Frame for Hand		Rotational to Linear, Linkages, Gears		Basic Structure, Pin, Brick	Pin, Brick		Pin, Brick		Batteries	NXT Electrical	Motor	Rotational to Linear, Linkages, Gears	Rotational to Linear, Linkages, Gears	Rotation, Time			Rotation, Time
Four Wheel Vehicle	Sturdy Frame for Hand		Rotational to Linear, Wheels	Steer dual	Basic Structure, Pin	Pin	Software, Sensors	Pin		Batteries	NXT Electrical	Motor	Rotational to Linear, Wheels	Rotational to Linear, Wheels, Medium	Time, Rotation			Time, Rotation
Introduction to LEGO Gears	Sturdy Frame for Hand		Gears		Basic Structure, Pin	Pin		Pin		Batteries	NXT Electrical	Motor	Gears	Gears	Direction			Direction
Snack Machine	Sturdy Frame for Hand	Rack and Pinion	Rotational to Linear, Track, Gears	Track	Basic Structure, Pin, Brick	Pin, Brick	Software	Pin, Brick	Rack and Pinion	Batteries	NXT Electrical	Motor	Rotational to Linear, Tracks, Gears	Rotational to Linear, Tracks, Gears	Light, Touch, Time, Rotation	Lamp	Lamp	Light, Touch, Time, Rotation
Three Wheel Vehicle	Sturdy Frame for Hand		Rotational to Linear, Wheels	Steer Dual	Pin	Pin	Software	Pin		Batteries	NXT Electrical	Motor	Rotational to Linear, Wheels	Rotational to Linear, Wheels	Time, Rotation			Time, Rotation
Treaded Vehicle with Sensors	Sturdy Frame for Hand		Rotational to Linear, Tracks, Gears	Steer dual	Basic Structure, Pin	Pin, Brick	Software, Sensors, Feeler Touch	Pin, Brick		Batteries	NXT Electrical	Motor	Rotational to Linear, Tracks, Gears	Rotational to Linear, Tracks, Gears	Light, Distance, Touch, Rotation, Time			Light, Distance, Touch, Rotation, Time
Walker	Sturdy Frame for Hand		Rotational to Linear, Feet		Pin, Brick	Pin, Brick		Pin, Brick		Batteries	NXT Electrical	Motor	Rotational to Linear, Feet	Rotational to Linear, Feet				
NXT-Sketch					Pin, Brick	Pin, Brick		Pin, Brick		Batteries	NXT Electrical				Rotation	NXT Display	NXT Display	Rotation

The columns of the table represent the classes in the Functional Common Basis. The rows represent the eleven devices analyzed. Each cell in the matrix represents the particular form-specific solution principle used by the corresponding device to accomplish the corresponding function. From the modified morphological matrix, the functions were totaled and grouped into six combined basic categories that represent the majority of the functions mapped. This grouping of the functions led to the LEGO Functional Common Basis shown in Table 3.

Table 3: LEGO Functional Common Basis

Basic	Examples	Sub Examples
Guide Position Steer	Steer Dual Motor	
	Steer Gear Box	
	Steer Caster Wheel	
	Track	
Stabilize Secure Couple Join	Basic Structure	
	Pin	Basic Pin Connections
		Pin Spacing
		Pin Right Angle
		Pin Vertical
		Pin Special Connectors
	Brick	Basic Overlapping
		Brick Sideways Connections
		Brick Right Angle
		Brick Vertical
		Brick Special
Change Convert	Rotational to Linear Walker	
	Rotational to Linear Wheel	
	Rotational to Linear Rack and Pinion	
	Rotational to Linear Linkages	
	Gears	Crown
		Spur
		Rack and Pinion
		Bevel
		Compound
		Worm
		Gear Up and Down
		Knob
Measure	Light Sensor	
	Sound Sensor	
	Touch Sensor	
	Distance Sensor	
	Rotational Sensor	
	Time	
	Feeler for Touch	
Activate	Walker	
	Tank Treads	
	Wheels - Size	
	Wheels - Caster	
Indicate Display	Lamp	
	NXT Display	
	Move Motor	
	Sound	

The examples and sub-examples originated from the modified morphological matrix, but additional function examples were added as needed. For example, functions that involve gears such as spur, worm, bevel, and others were listed for many of the designs. To better cover the concept, all the major LEGO gear combinations are included as sub-examples.

To evaluate the LEGO Functional Common Basis, several projects were examined that were created in LEGO Technics. The designs analyzed came from a variety of sources in the LEGO community including Tufts University's LEGO engineering site[17], LEGO Education [18], and The LEGO User's Group network[19]. The building instructions for these designs were examined to identify the major functions the product demonstrated. The functions were then mapped to the LEGO Functional Common Basis to verify the completeness of the basis. The successful mapping of the projects to the LEGO Functional Common Basis suggests that the next logical step in the refinement of the basis is feedback from users.

4.2 Design with LEGO Tool – Interface

To implement an active interface for the LEGO Functional Common Basis, an HTML-based tool was created. The Design with LEGO Tool is available as a part of The University of Texas at Austin Cockrell School of Engineering DTEACh website, currently at www.engr.utexas.edu/dteach/resources/dlt/. The DLT begins with a top-level page that explains how to use the tool, shown in Figure 2.

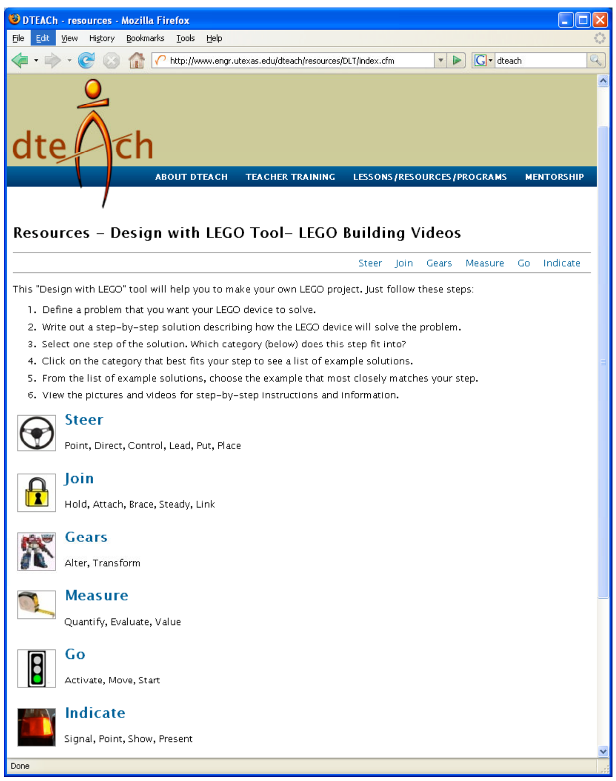

Figure 2: Top level page of the Design with LEGO Tool

The tool then allows the user to select DLT LEGO Classes. The Design with LEGO Tool was first evaluated in a feedback session with an education expert who was a teacher for over 20 years and is now an education specialist. The expert was asked to give constructive feedback on an alpha prototype of the tool[20]. Her feedback led to changes in the instructions, changing the class names to better suit the common vocabulary of K-12 teachers and students, and the addition of synonyms under the six category titles. The selection of a LEGO class links to a page that lists examples of that class of functions, as shown in Figure 3.

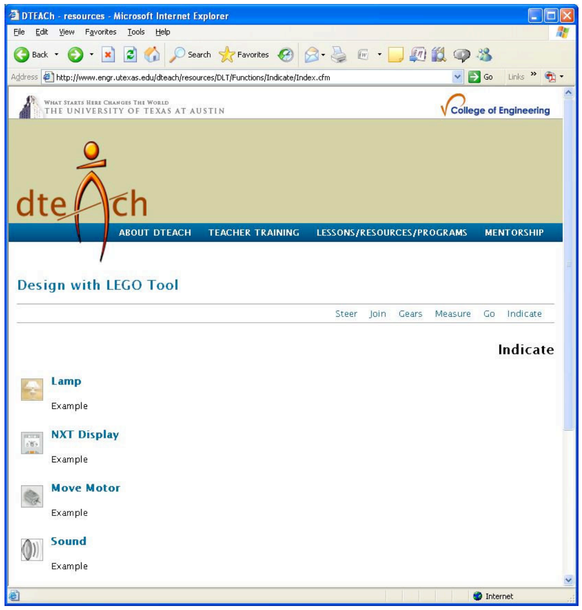

Figure 3: Second level page of the Design with LEGO Tool

Selecting one of the examples transfers to a page that shows a video or pictures of an example of that function implemented in LEGO Technics. Figure 4 shows one frame of a video that plays after selecting "Indicate – Sound."

Figure 4: Example page of the Design with LEGO Tool

Links to sample NXT programs and building instructions for the examples are provided on the page for download. The videos are twenty to fifty seconds long, focusing on demonstrating the function with a LEGO Technics device. The videos were produced with an Apple MacBook Pro, iMovie and Adobe Flash software. In three areas, Gears, Pins, and Studs, sub-examples were used to organize a comprehensive list of examples and demonstrate the second level of organization.

5.0 Deployment and Evaluation of the Design with LEGO Tool

As a part of the DTEACh Program, the Design with LEGO Tool was introduced to the teachers during the design step. The teachers were told that the tool was available to them for assistance in building with LEGOs. When the teachers worked on their design projects, they were reminded that the tool was available to them.

To evaluate the teachers' responses to the Design with LEGO Tool, the tool was used in the June 23-28, 2008, and July 21-25, 2008, DTEACh sessions and evaluated with an end-of-program survey. The survey included questions to assess the teachers' opinions of the Design with LEGO Tool.

During the June 23-28 training session, the Design with LEGO Tool was demonstrated to teachers and they were told they could use it during their project design sessions. A limited number of teachers responded to the training as shown in Table 4.

Table 4: DTEACh Training Workshop June 23-28 DLT Survey Responses (N=6)

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Prefer not to
I have used The Design with LEGO webpage tool.	2	3	1	0	0	0
I feel that The Design with LEGO webpage tool is useful.	4	1	1	0	0	0
I plan on using the Design with LEGO webpage tool in the future.	4	1	1	0	0	0
I feel that the Design with LEGO webpage tool is helpful at assisting me with LEGO projects.	4	1	1	0	0	0

The majority of the teachers strongly agreed that the Design with LEGO Tool is useful and they plan on using it in the future. Initial concerns that the tool would not be useful or would be too complicated for teachers appear to be unfounded. Even though the sample size is small, the teachers who interacted with the tool found it useful. The data indicate that all the teachers who used the tool plan to use it in the future. This provides evidence that the teachers think the tool will be useful to them.

In the second DTEACh training session on July 21-25 2008, the Design with LEGO Tool was demonstrated briefly to the participants. The teachers' responses to the tool are shown in Table 5.

Table 5: DTEACh Training Workshop July 21-25, 2008 DLT Survey Responses (N=20)

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Prefer not to answer
I have used The Design with LEGO webpage tool.	6	2	1	4	1	6
I feel that The Design with LEGO webpage tool is useful.	6	3	1	1	0	9
I plan on using the Design with LEGO webpage tool in the future.	7	4	0	1	0	8
I feel that the Design with LEGO webpage tool is helpful at assisting me with LEGO projects.	6	3	2	0	0	9

During this training session, the Design with LEGO Tool was only briefly introduced. The data reflect the responses of all the participants in the workshop, although more than half the teachers expressed that they had not used the Design with LEGO Tool webpage. This lack of interaction with the webpage for some participants was due to a logistic issue with the workshop. This data exposes the challenge of enticing teachers to try the tool. Is the webpage interface daunting to some teachers? This needs to be investigated. All of the teachers who used the Design with LEGO Tool webpage expressed that they plan to use the tool in the future. Four of the teachers who only saw the demonstration of the Design with LEGO Tool webpage but did not use the tool also plan to use it in the future. Overall, the teachers in all sessions expressed interest in using the DTEACh 5-Step figure and Design with LEGO Tool webpage in the future.

6.0 Conclusion and Future work

The Design with LEGO Tool was used in two DTEACh workshops. Very limited survey data were collected, but the responses were very encouraging. The Design with LEGO Tool was considered useful and the teachers plan to use it in the future. Overall, the tool was very well received, but evaluation of the tool by a larger population is needed.

One issue that arose with the research is engaging teachers in learning function-based design. The Design with LEGO Tool is meant to support individuals who are implementing function-based designs with LEGOs. Problems with motivating teachers to learn the functional approach to design arose in the analysis of the tool. One potential way to motivate the teacher is to teach the concepts of functional design in the videos that provide instructions for building a LEGO design. During the focus group, the teachers requested videos on building LEGO designs. Future work could determine if the concepts of functional design can be taught via the videos.

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