# Proof of Concept Study of Trade Space Configuration Tool for Spacecraft Design

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Spacecraft design is a very difficult and time consuming process because requirements and criteria are often changed or modified as the design is refined. Accounting for these adjustments in the design constraints plays a significant role in furthering the overall progress. There are numerous aspects and variables that hold significant influence on various characteristics of the design. This can be especially frustrating when attempting to conduct rapid trade space analysis on system configurations. Currently, the data and designs considered for trade space evaluations can only be displayed by using the traditional interfaces of Excel spreadsheets or CAD (Computer Aided Design) models. While helpful, these methods of analyzing the data from a systems engineering approach can be rather complicated and overwhelming. As a result, a proof of concept was conducted on a dynamic data visualization software called Thinkmap SDK (Software Developer Kit) to allow for better organization and understanding of the relationships between the various aspects that make up an entire design. The Orion Crew Module Aft Bay Subsystem was used as the test case for this study because the design and layout of many of the subsystem components will be significant in ensuring the overall center of gravity of the capsule is correct. A simplified model of this subsystem was created and programmed using Thinkmap SDK to create a preliminary prototype application of a Trade Space Configuration Tool. The completed application ensures that the core requirements for the Tool can be met. Further development is strongly suggested to produce a full prototype application to allow final evaluations and recommendations of the software capabilities.

## Nomenclature

CAD    = Computer Aided Design
CEV    = Crew Exploration Vehicle
C.G.    = Center of Gravity
CM    = Crew Module
CSS    = Cascading Style Sheets
HTML    = Hyper Text Markup Language
ISS    = International Space Station
JSC    = Johnson Space Center
LEO    = Low Earth Orbit
Pro/E    = Pro/ENGINEER Modeling Software
SDK    = Software Developer Kit
XML    = Extensible Markup Language

## I. Background

NASA is currently designing new spacecraft with the goal of returning humans to the moon and going onward to Mars and other destinations within the first half of the century. This new mission has given birth to the Constellation Program, which will be made up of many new spacecraft and surface hardware to allow long duration stays. The Orion Crew Exploration Vehicle (CEV) is arguably the most important aspect of this program because it

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will be used to transport humans to Low Earth Orbit (LEO) and to return them home safely. The new Ares I and Ares V will serve as the two launch vehicles to lift all the new hardware off the ground. For lunar missions, the Ares



**Figure 1. Cutaway View of Orion CM Capsule.** *Aft Bay Subsystem components are shown around the bottom shell of the capsule, just above where the heat shield begins.*

V heavy cargo lifter will launch first to deliver the Earth departure stage, Altair Lunar Lander, and lunar surface hardware to LEO. Not long after, the Ares I will be launched carrying the Orion CEV to rendezvous with waiting spacecraft. The Orion CEV will also be used to deliver crews and cargo to the International Space Station (ISS).
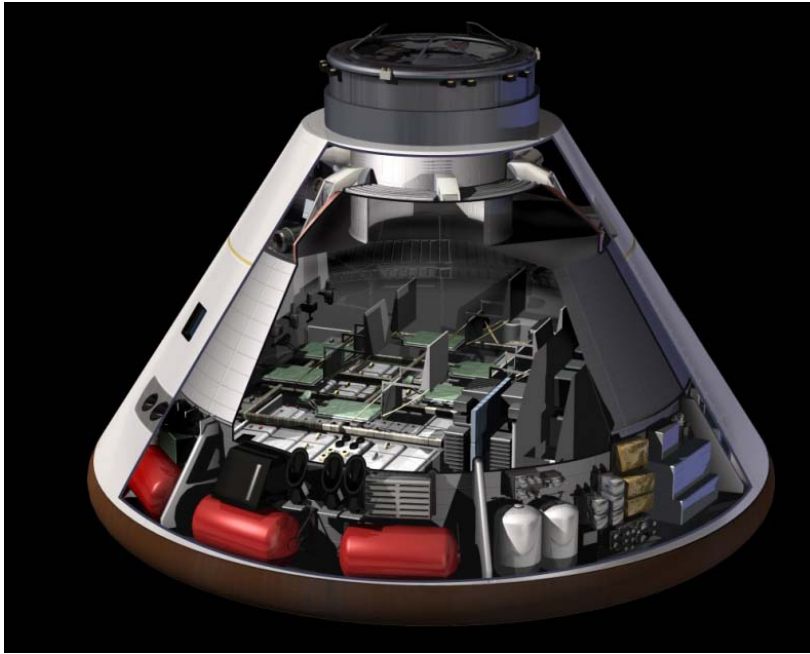
The CEV consists of three connected components, the Service Module, the Launch Abort System, and the Crew Module (CM) which is shown in Figure 1. As the name suggests, the CM will be a habitable capsule, similar to the heritage design of the Apollo capsules, but slightly larger by size comparison. The similarity ends beyond appearances though, as the CM will be outfitted with state-of-the-art technology and modern hardware proven from the space shuttle. The spacecraft will be modifiable to

allow it to be used either to dock with the ISS, or to join with additional craft for a lunar or Mars mission. The capsule itself will also serve as the Earth re-entry vehicle upon completion of all missions.

The Aft Bay Subsystem is the name given to the components that are placed just inside the lower outer ring of the internal capsule. This subsystem consists of all the components that do not need to be located within the pressurized vessel of the CM cockpit. Some of the more well known components consist of the oxygen tanks, the star trackers, and the rotational control system thrusters and propellants.

## II.   Introduction

Systems architecture and integration is a very critical aspect in the design of any product that requires engineering. This is especially true in the design of spacecraft. Every component and specific feature that goes into a design will have a cause and effect relationship with many other components and features of the design. As a result, there are often many different variables that must be understood and accounted for to be able to fully integrate all of the necessary elements in an overall design. Two main steps must take place in order to allow for a successfully integrated design. The first step is to develop an understanding of all of the possible scenarios and relationships that can be present. Then, the second step is to incorporate and apply this knowledge for all of the scenarios to achieve the most feasible design. These are the critical drivers that allow for an integrated product.

The second process is the more complex, and ultimately the most important step that must be addressed in order to produce a complete design that accounts for all variables. This is the critical step where trade studies are conducted to determine the most optimal method to combine and integrate the necessary factors. In spacecraft design, this is truly the most difficult and time demanding stage of development because often there are so many factors present that the amount of combinations between them can seem infinite. As a result, a majority of the time may be spent on this process alone by simply trying to determine all of the possible combinations and then developing constraint criteria to ultimately arrive at a final solution. Since the number of combinations can be infinite, this final solution may only represent the best resolution that was considered rather than being the most optimum solution. A better qualitative and quantitative approach is needed in order to improve this process to help minimize the amount of time and effort that are required.

A proof of concept study was conducted on this process to explore a new software program known as Thinkmap SDK (Software Developer Kit)[1]. Thinkmap SDK is a program that offers interactive dynamic visualization of

complex data. It provides a new approach that relies more on qualitative methods to better illustrate relationships between key factors that normally cannot be shown in traditional interfaces. This aspect can lead to a new and different way of displaying information that can often reveal solutions not normally apparent. The Orion CM Aft Bay Subsystem was used as a test case for this study with the goal of developing a Configuration Trade Study Tool to improve the overall center of gravity (C.G.) analysis of the capsule and its components.

## III. Research and Preparation

The Aft Bay Subsystem is located around the outer bottom portion of the Orion CM capsule. It is made up of all the hardware components and elements that do not need to be in the pressurized cabin, but are still covered by the heat shield and the outer shell of the spacecraft. Some of the components consist of the oxygen tanks, star-trackers, control thrusters, various avionics systems and batteries, and all of the necessary electrical wiring and plumbing tubes that connect everything together. Many of these components carry some considerable mass with them, and as a result their respective locations play significant roles in the overall C.G. of the capsule. However, the design solution doesn't come from simply arranging everything so that the heavier components are closer to the needed C.G. location. There are many more complicated variables that dictate where and how the components can be placed and arranged in addition to mass and overall orientation. These factors can consist of outer dimensions and clearance of components, power requirements, thermal exposure, minimizing required length of wiring or tubing connections, etc. Varying these factors makes for very complex design scenarios and intricate trade studies to move towards a final solution. As a result, this test case serves as a prime example to demonstrate how useful a Configuration Trade Study Tool would be for a complicated design problem.

The initial steps were aimed at exploring the various options that could offer new approaches to the problem of finding a better tool for trade configuration studies. Currently, only Computer Aided Drawing (CAD) models and Excel spreadsheets are available for use in the design and development for projects like the Orion CM Aft Bay Subsystem. As a result, alternative choices needed to present new or different features that could not be found using CAD or Excel. Thinkmap SDK presented the most viable option not only because it offered better clarification of complex data, but also because it theoretically combined both CAD and Excel interfaces. The issue with using CAD models alone is that while they can provide an accurate visual layout of all the physical components and necessary connections, there is no easy way to determine how the whole subsystem will be affected after a modification has been made. This discrepancy can and is often alleviated through the paralleled use of a spreadsheet with programmed formulas; however this does not always account for everything. Additional research was conducted on Tradespace Modeling Tools that had been produced for rapid design development of deep space robotic missions. However, these tools only offered the same potential present in a programmed Excel spreadsheet. Thinkmap SDK offered a much more promising interface that could take data from a spreadsheet input and then visually depict relationships within the information.

## IV. Preliminary Development

Thinkmap SDK uses an XML-based (Extensible Markup Language) configuration through a Java Applet to allow for the rapid production of data-generated visualizations. It can simply be compared to something found on an interactive website application, however it is much more focused on displaying information in the best possible manner rather than only trying to achieve an aesthetically pleasing output. Since most of the code used for modifications were written in this markup language, it became necessary to become familiar with XML, HTML (Hyper Text Markup Language), CSS (Cascading Style Sheets), and JavaScript. The overall code is written to be more user-friendly to modify than any of these particular languages, however many of the code's attributes originate from these so a familiarity is required.

The process for developing a personal application using Thinkmap SDK is based off a generic demo titled "Movies of the 1980's" that portrays an interactive spider web layout of many popular 1980 movies. The demo presents the movie titles and then shows relationships and classifications between genres, directors, as well as actors and actresses. A step by step tutorial is provided that covers all the necessary underlying code that produces the Thinkmap display. The job of the developer is to become familiar with all the statements and functions that make up the product so that modifications and alterations can be made to adapt it for their purposes.

Initially, attempts were made to make significant changes in the code in order to adjust it for the intentions of modeling the entire Aft Bay Subsystem. While the tutorial guide was helpful, this process eventually became overwhelming and cumbersome to modify everything needed to accurately display the subsystem as a whole. Too many alterations were needed in the code, and often more time and effort was spent on troubleshooting errors rather than focusing on actual analysis of the development process. In order to alleviate this, attention was turned to

working alongside the Thinkmap support staff to address issues in a better manner. After feedback had been given from the support staff, a requirements list was prepared to allow more accurate analysis of what capabilities were needed in order to make the Tool useful.

The overall requirement to make the Tool useful was that it needed to provide an interactive user environment that would be easy to use and understand. More specifically, it needed to clearly show the relationships and driving factors that would be significant in the trade study for C.G. analysis. These elements consisted of classifications within the subsystem, location of the components within the vehicle, necessary connections between components (structures, electrical, etc.), outer dimensions of components, and most importantly the mass of components. To take it a step further, secondary and more intuitive capabilities would be assessed as well. Some of these consisted of being able to show the orientation of the component's shape, illustrating the clearance between each component, determining the needed length of any connection lines based on required distance, and lastly allowing the user to actively modify the location of a component in order to see how all the previous factors would be affected. The first step that was taken to begin the proof of concept study was to develop a simplified model of the aft bay subsystem and attempt to determine if all the basic requirements could be met.

## V.   Prototype Application for Simplified Model

In keeping with the Orion CM aft bay subsystem test case, the simplified model was developed to mirror some of the more significant elements that determine the overall C.G. An outline of this set-up is illustrated in Figure 2, which shows a cut-away section view looking down towards the aft direction of the capsule. The outer boundary represents the sloped outer wall of the aft bay and the inner boundary represents the pressure vessel of the CM. Within this there are three generically labeled objects that represent the types of components that exist in the aft bay. These labels are the Avionics Box, the Battery, and the Oxygen Tank. Each of these objects carries the two characteristics that are needed for the C.G. calculation, a coordinate location and a mass. For the purposes of this model, arbitrary values were assigned for these characteristics that have no reflection on actual locations within the aft bay. The additional components of Electric Wiring and Plumbing Pipes were added to simulate the additional factors that must be accounted for. Both of these components have a length and unit mass characteristic. The length of the wire or tube is directly dependent on the distance between the two components it must connect. The total mass is then determined based on this length and the provided unit mass. The



**Figure 2. Overview of Simplified Model for Aft Bay Subsystem.** *Consists of generically labeled components and characteristics. View looking at cutaway towards aft of capsule, just above the heat shield.*

simplicity of this model held two advantages in developing the prototype Trade Study Configuration Tool. First, it focused directly on ensuring that the most critical requirements could be met. Second, it allowed for easy explanation and comprehension to both the Thinkmap support staff and any others not familiar with the aft bay subsystem or Orion CM.
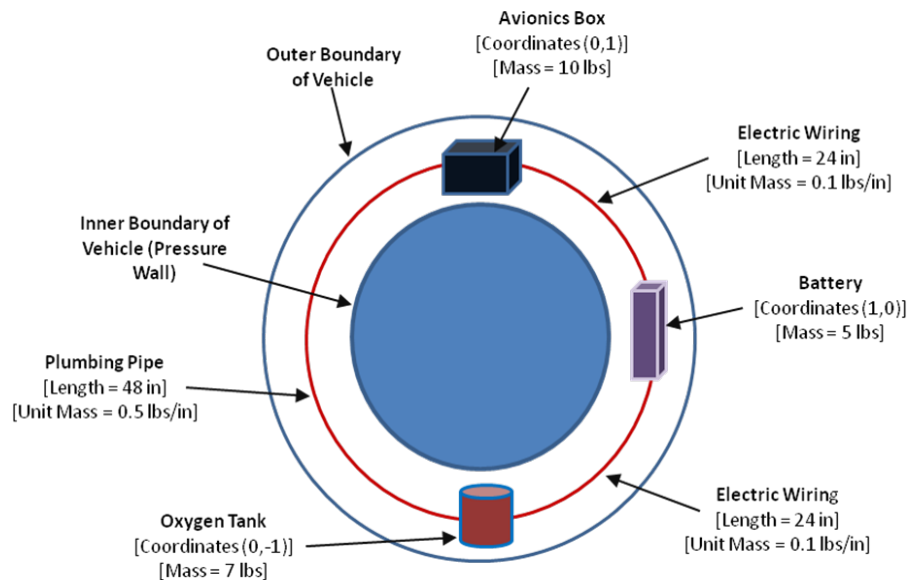
The model was successfully produced using the Thinkmap SDK and utilizing the "Movies of the 1980's" tutorial. After some consideration of the hierarchy layout that had been initially suggested by the support staff, the spider web layout was ultimately chosen. The final output produced an interactive environment that related the significant elements through the Thinkmap system of nodes (objects) and edges (lines). The opening screen for this application is shown in Figure 3. The initial center node that appears at the application start-up is the Avionics Box

component. As a result, all of the elements, characteristics, and other components that are directly related to the Avionics Box are displayed as well. The web layout visually shows that the Avionics Box is directly connected to the Battery through Electric Wiring and the Oxygen Tank through Plumbing Tubes. The main drivers for these



**Figure 3. Main Display of Model Application.** *Opening layout of model is centered on Avionics Box node. Primary and secondary relationships are shown as well. © 2009 Thinkmap, Inc. <http://www.thinkmap.com>*

connections are displayed as well through the Tube Length and the Wire Length. The C.G. characteristics of Mass and Coordinates connect all the components and objects as well. The web layout is programmed so that the more directly related nodes are closer to the Avionics Box (Mass, Coordinates, Tube Length, and Wire Length) and then the secondary connecting nodes are further away (Oxygen Tank, Battery, Electric Wiring, and Plumbing Tubes). Additionally, the nodes are programmed to provide more instant visual information to the user. This is evident in the
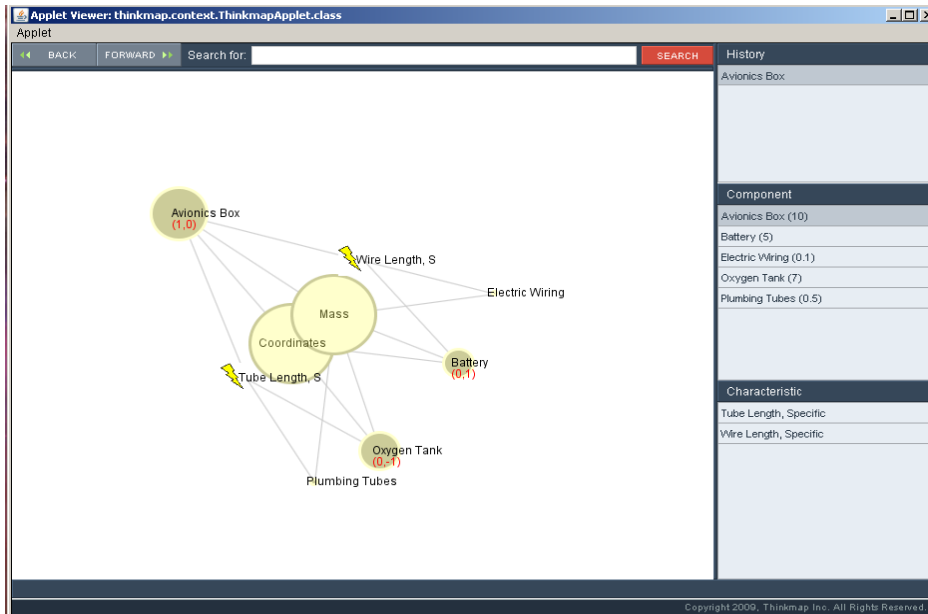
red labels below the object node titles that display the coordinates as well as in the size of the circles that illustrate the relative mass (or significance) of the objects. Since the Mass and Coordinate nodes are the most important in determining the C.G. of the model, these are displayed with the largest circles. The circles for the remaining object nodes are sized with respect to the greater mass of the object, hence the Avionics Box has the larger circle compared to the lighter Oxygen Tank and continuing down in mass to the lightest Electric Wiring and Plumbing Tubes.

As stated previously, the center model is fully interactive to the user. The nodes and edges can be clicked and dragged to new locations to better show information that may be cluttered. Nodes can also be chosen by clicking on them to bring them to the center of the map and to adjust the layout to show only the components and characteristics that directly relate to that node. Figure 4 shows the application screen and the new map layout that appears after clicking on
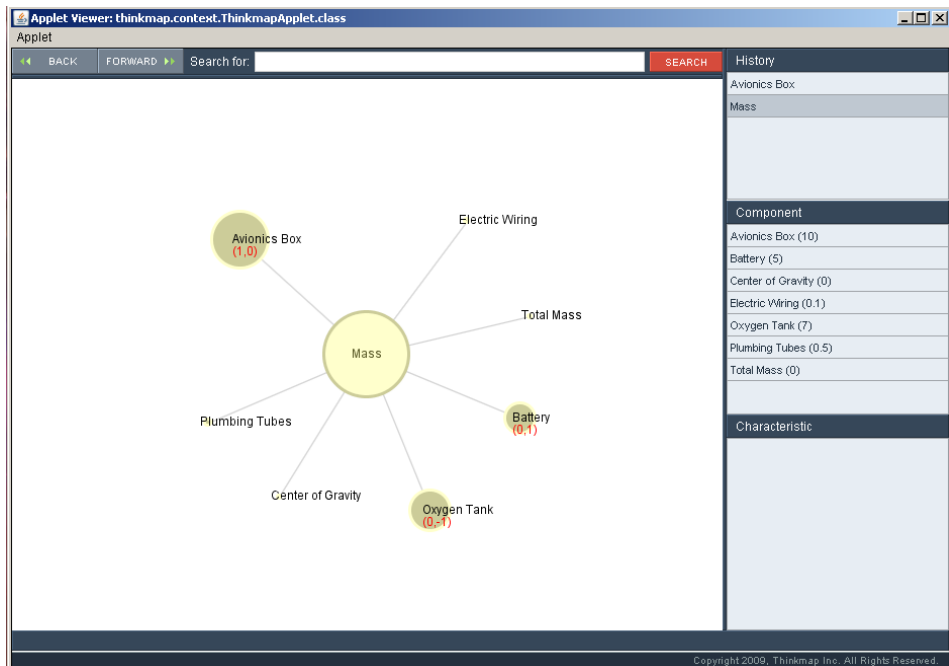


**Figure 4. Following Display of Model Application.** *Model is centered on Mass node after clicking on it in previous display. Only primary relationships are shown. © 2009 Thinkmap, Inc. <http://www.thinkmap.com>*

the Mass node. Since the Mass node is a significant characteristic (like the Coordinates node), only the nodes that are most directly related to it appear in the new map layout in order to reduce clutter and non-essential information. As a result, the Tube Length and Wire Length nodes no longer appear. For the same reason, the new nodes titled Center of Gravity and Total Mass appear since they represent computations that depend directly on the mass of all components. The list panels on the right side of the application are provided to further organize the information that is present in the interactive center web layout. The History category is shown at the top right; this provides a quick way to both see and be able to return to previous visited nodes. Here it shows that the first visited node was the Avionics Box, and the second and current node is Mass. The history can also be revisited by using the "Back" and "Forward" navigation buttons at the top left corner of the application. Below the History category is the Component category that provides reiterated information from the web layout in list form for further clarity. Each of the nodes is listed and their respective mass, if applicable, is shown next to them in parenthesis. This serves an important function to a user by allowing them to relate an actual value to the illustrated circle sizes. Below the Component category is the Characteristic category. This is currently empty because there are no characteristics displayed, however in Figure 2 both the Tube Length and Wire Length labels are shown along with the definition of "Specific" for further understanding. The last and probably one of the more useful features is the "Search" tool bar that is located at the top center of the application. The user can type keywords to search for a specific node label and then be able to click on the correct search output to quickly navigate to the node of interest. This function will likely be utilized quite often for the full prototype of the aft bay subsystem when there will be much more information contained within the application.

## VI.  Outcome and Future Work

The finished product for the simplified model demonstrated that the core requirements can be met for the purposes of developing a Configuration Trade Study Tool for the Orion CM Aft Bay Subsystem. The most important of these was that an interactive and dynamic user environment that was easy to utilize and understand could be achieved. All of the significant elements and relationships for the simplified aft bay model were shown very clearly with the help of the spider web layout. Since the primary capabilities were demonstrated to be possible, additional development should be taken to further assess the software. The best argument for justifying the use of the Thinkmap SDK will be made when it can be shown that more intuitive means of trade studies are possible. These capabilities consist of being able to show the orientation of the shape of the objects, defining the clearance between objects, and determining the length needed for connections based on distance. In addition to all these, the most significant justification would be if the interface could be actively modified by the user during the running of the application. This would allow the user to conduct trade assessments in real time by adjusting various objects and components to see how all additional elements would be affected. Future work should be focused on either improving the current model of the Configuration Trade Study Tool or by creating a new application and incorporating the lessons learned. The direction of this development must aim at producing a full prototype for the Orion CM Aft Bay Subsystem that will allow for final evaluations and recommendations.

## VII.  Conclusion

A Configuration Trade Study Tool promises great reduction in both the time and effort required in the overall design of spacecraft. All of the elements and features that go into spacecraft design make for a complex collection of information consisting of numerous intricate relationships. At the same time, conducting trade studies are a crucial part of the design process to ensure that specific criteria and constraints are satisfied in the best optimal manner. It can be an overwhelming and slow procedure to systematically go through all the various design options. This proof of concept study has proven that the Thinkmap SDK can meet the core requirements to determine if its capabilities would be useful for a trade study tool. However, it will likely take much more development to produce a suitable prototype for the aft bay subsystem in order to conduct final recommendations on the application's usefulness. Nonetheless, this additional endeavor should be more than warranted considering the amount of effort and time alone that is currently spent on carrying out trade studies through the use of CAD models and spreadsheets. Even if it is ultimately determined that the cost of the software cannot be proven to offset the burden of current trade study methods, the development itself will likely produce new approaches and procedures that can be utilized. In this case, the results of the study will likely be revisited and may be utilized as an appropriate starting point for further proof of concept studies in the future. The final proposal of this study is to strongly recommend that further development be conducted to assess additional capabilities of the Thinkmap SDK through production of a completed prototype Configuration Trade Study Tool for the Orion CM Aft Bay Subsystem.

## Acknowledgments

## References

[1]© *2009 Thinkmap, Inc.*, URL: http://www.thinkmap.com/ [cited 7 August 2009].