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Information Visualization for Product Lifecycle Management (PLM) Data

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Abstract

Enabling users to explore the vast volumes of data from different groups is one of product lifecycle management (PLM)'s goals. PLM must solve such problems as isolated "Islands of Data" and "Island of Automation"; the massive data flow of distanced collaborative design, manufacturing, and management; and the incapability of interpreting and synthesizing data from different perspectives.

This paper proposes a new approach from a different perspective: information visualization and visual analytics. An interactive information visualization approach was demonstrated in order to help designers gain insights into massive data and make appropriate decisions. Suggested are possible visualization methods for PLM data- structural visualization, temporal visualization, geospatial visualization, 3D model visualization, and multidimensional visualization. This idea is then demonstrated by a case study of developing an Internet-based information visualization system to visualize the Remote Control Helicopter.

Introduction

Product lifecycle management (PLM) is the process of managing the entire lifecycle of a product from its design and production to service support and retirement. Nowadays, PLM has become a mission-critical component for manufacturers, and it forms the information backbone of a product and its company[1]. However, facing the explosion of digital product data and different user requirements, the development of PLM is limited by (1) isolated "Islands of Data" and "Island of Automation," (2) the massive data flow of distanced collaborative design, manufacturing, and management; and (3) incapability of humans interpreting and synthesizing data from different perspectives. The current state severely limits communication across different user groups and discourages collaborative management and concurrent product development.

3D models are used in almost all current PLM systems, which provide a realistic representation of the product in context. However, there are disadvantages in using these models. First, some parts may be invisible because they are covered by other components. People can choose section views to show interior details, but they may miss part of the external features of the object. Second, although photorealistic rendering makes the final product image look nice, the real material may be covered by the appearance of output. Moreover, some materials may have the same look in a 3D model, but they may have different weight and strength value in the real world. Lastly, 3D model visualization is unable to show metadata such as material, weight, and price.

Now PLM starts to combine 3D models with 2D visualization graphs. Teamcenter allows designers and engineers to view basic 3D measurement and 2D markup tools in a single environment. ENOVIA not only offers 3D visualization tools, but also provides 2D visualization services such as line charts and tree graphs. However, these provided 2D visualizations are still very simple in our view. The full potential of visualization has not been utilized. We believe it is essential to embed 2D visualization tools within 3D models. The integration will enable product lifecycle participants to understand and analyze data quickly and accurately, resulting in shortened development times and lower lifecycle costs.

Growing out from the fields of Information Visualization (Infovis) and Scientific Visualization (Scivis), Visual Analytics (VA) promotes the development of science and technology in analytical reasoning, data transformation, and representations for computation and visualization[2]. VA has been shown to be efficient at handling massive, dynamic, and conflicting data. With the help of VA, people can synthesize information into knowledge, derive insights from data, and provide timely and understandable assessments. However, very few PLM tools currently provide sufficient visual capabilities to help users analyze abstract data. Therefore people have an absence of an exploratory "middle ground" to connect the PLM with VA technologies. Beginning in the 1990s, Internet-based PLM systems have provided a more flexible platform for users to share and work on data. The focus of this paper is to enable a new class of product data analysis tools by integrating VA technologies and Internet-based data communication into PLM. We envision that the innovative integration will accommodate communications across different groups, catalyze creative design ideas, support the exploratory data management process, and thus improve the full product lifecycle from design to manufacturing and beyond.

Current Visualization Attempts to Support PLM Data

PTC offers a robust set of 2D and 3D visualization solutions called Windchill Visualization Services (WVS) that enables users to view components by using Creo View[3]. Siemens provides two solutions for visually analyzing the product during its design process. The first one is NX that uses HD3D Visual Reporting from metadata to help designers understand design issues. With different color-coded tags and "see-through" settings, users can see the inside components of 3D models and comprehend data quickly[4]. With the integration of product views and 2D snapshots, Teamcenter's lifecycle visualization can send CAD data to the stand-alone application viewer or the Lifecycle Viewer to provide a complete view of the whole assembly[5].

Almost all these projects use spreadsheets, basic information diagrams, and tree widgets to display the product information. However, very few existing PLM systems adopt sufficient visualization technologies to support data interpretation and management. Some pioneer projects include visualizing product variations and configurations[6]; the use of VA approaches to predict the effects of different parameters in car engine design[7]; applying interactive visual analysis to support simulation runs in a hybrid-vehicle design[8]; and managing the flow of iron and steel associated with car production[9].

Currently, product data management (PDM) technology has been used in many different manufacturing enterprises to organize design files and processes. With JT Open, WebGL, or HTML5, some researchers propose that PDM provides a collaborative environment by the means of dynamically exchanging and collaboratively visualizing 3D models. Some researchers have created an interactive visualization platform for large aircraft development[10]. The interactive platform provides evolutionary information in product lifecycle stages that enable the chief project engineer to accurately make decisions. Semantic mapping approach is also used in aircraft tooling design. With the use of Teamcenter Engineering (TcEng) programming technology, the semantic transmission between aircraft tooling and inventories is highly improved[11].

Also, several projects use Internet-based product information sharing and visualization aiming to conquer the issue of "Islands of Data"[12, 13, 14, 15]. The Web can be used at different stages of the PLM cycle: such as sharing product information and knowledge during the design stage[12], managing product data with the simultaneous development[13], and monitoring the performance of the working system[14]. A combination of WebGL and X3D technology allows the successful visualization of CATIA models to the Web. It facilitates Web-based collaboration and 3D mediated communication in PLM[15].

VA research has been growing rapidly in recent years and has started to transfer from research labs to real applications in industry. For example, Purdue's VACCINE center has developed a system to analyze the historic response of U.S. Coast Guard search-and-rescue operations in the Great Lakes. This tool can help decision makers allocate resources for rescue resources[16]. Wang et al[17] develops a VA system to help bridge managers analyze bridges and plan maintenances. Wong et al[18] created a visualization system called GreenGrid to examine power system information through semantic encoding, multilevel graph visualization, and force-directed layout. Jigsaw[19] and CZsaw[20] enable users to make sense of a large collection of text. They offer a collection of visualizations to detect the connection among alternatives. With document view, scatter-plot view, history view, and dependency graph, these visualizations can help users examine the connection between entities and support analytical strategies. Such VA systems have been widely adopted in many domains. But it is still rare to see the application of VA on PLM.

Possible Information Visualizations for PLM Data

An effective PLM environment enables an enterprise to gain deeper insights into product data and make better decisions. Manually reading the massive amounts of data created in the product lifecycle is simply not viable. In the section below, we discuss several information visualization techniques based on Shneiderman's information visualization taxonomy[21] and its possible usage for visualizing PLM data. With these technologies, users would comprehend different kinds of data easily. It will also help users identify problems and guide the direction for future product improvement.

Structural visualization

Tree graphs for hierarchical structure: Tree graphs are a group of linked nodes, and each node (except the root) has a parent node and possible subtrees of child nodes (the first image from left in Figure 1). Many PLM systems use a tree to visualize the products' assembly hierarchy. Teamcenter's BOM (bill of materials) relation browser views BOMs as an expanding tree with layered nodes. Inside nodes are 2D screenshots of the parts or subassemblies. The product specification tree in CATIA displays the component structure as a tree with different icons. Aras EPLM provides a deep vertical tree layout for the BOM structure browser and product structure browser. With the tree graph of the product family, the user can easily see the hierarchical structure of the product.

Sunburst partition to visualize quantitative measurements: Extended from a general tree graph, a sunburst graph is a radial visualization technique to visualize hierarchical data. The root node is in the center of the graph. People can get the child data with different arcs by adding additional layers (the second image from left in Figure 1). Each arc represents an assembly in a product's hierarchical structure. Sunburst demonstrates hierarchies shaped like donuts, and one arc represents to its related value. The direct connections among nodes are not as clear as regular tree graphs. But the length of arcs provides an additional dimension to represent quantity measurement of the part/subassembly.

Network graphs to visualize network relationship: Many times the connections of entities are complex. Instead of a tree structure's one (parent) to many (children) relation, network connections are many to many, just like the physical connections of many parts inside one product. One part may be connected to many other parts, and may have been connected by many parts, which forms a *network*. Various types of network graphs visualize such types of data. A dependency wheel is a powerful visualization tool to explore directed relationships among a group of entities (the third image from left in Figure 1). In the disc, each chord diagram represents a connection between two nodes. This visualization tool also demonstrates simple interactivity by using a mouse hovering on a chord to mask other dependencies and highlight the selected dependencies with different colors.

Matrix diagram to visualize strengths of relationships: Similar to a dependency wheel, a matrix diagram is another powerful tool to show the strengths of relationships among two or more groups. The matrix diagram is created in a table with rows and columns corresponding to the correlated items. The rest of the cells contain symbols or numerical values to indicate the strengths of relationships. Color or saturation can be used to denote the relative weight to the evaluation, and they make it much easier for users to comprehend the relationship (the forth image from left in Figure 1). Comparing the messy linkages in a dependency wheel, the connections may show unique visual patterns that reveal some important product assemble information.

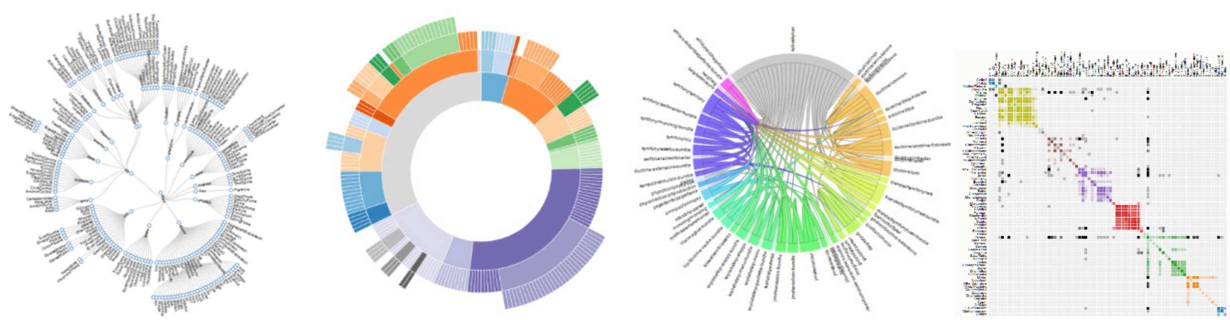

Figure 1: Possible Structural Visualization Methods[22]

Structural visualization is useful to display hierarchy and network data in PLM. By differentiating node properties, such as color, size and shape in tree graphs, researchers are able to represent different part attributes such as weight, size, and material. For the proportional size of the nodes in a sunburst, they can display the quantitative metrics of data such as mass, lead-time, or cost. The thickness of the curve in a dependency wheel or different colors between nodes in a matrix diagram can designate the strength of the connection among components. Thus engineers can make appropriate design decisions, such as which parts have shorter lifespans or weaker links.

Temporal visualization

The temporal visualization method allows researchers to visualize the temporal distribution of objects. Arc diagrams are well suited to display the chronology of nodes (Figure 2, top). By drawing arcs between nodes, the visualization shows node-to-node relationships and makes it clearer for users to see how the information may evolve. With stacked layers, a stream graph can display time series data in a flowing river shape (Figure 2, bottom left). Constraining the thickness of the stacked graph also enables users to get easy access to different types of data. A connected scatter plot is another good choice to visualize data in real time (Figure 2, bottom right). A simple linear relationship may be used to represent the work-flow information related to the products.

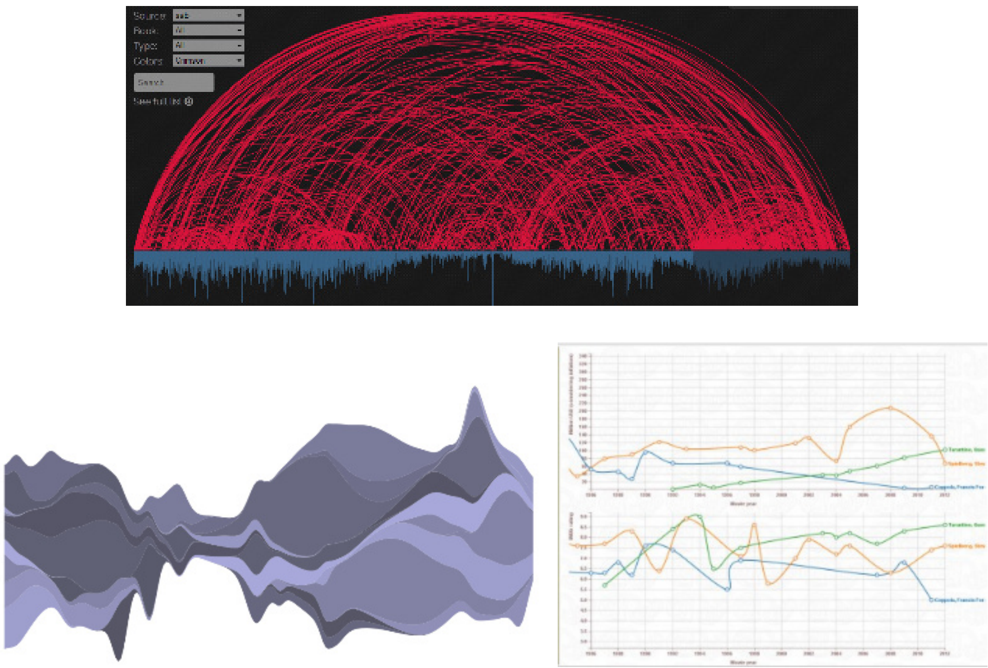

Figure 2: Possible Temporal Visualization Methods[22]

Temporal visualization is useful to display the connection between time series data. Users can simulate product maintenance and see the cost changes over time, thus enabling them to plan ahead. These graphs can provide a set of prebuilt analytics that facilitate the management to maintain cost, quality, and lead time targets with temporal information. It would help designers reduce risks and raise product quality before the designs are used for full-scale manufacturing.

Geospatial visualization

Geospatial visualization helps users explore location-related data in a map view. Different kinds of color progression are used in choropleth maps to compare data values properly (Figure 3, left). By adding symbols or graphs such as circles, histograms and pie charts over an underlying map, users can create a proportional symbol map that enables them to visualize the proportion of each area (Figure 3, middle). A dot distribution map uses dot size and spacing to communicate the geographic distribution of events (Figure 3, right). Geospatial visualization is a natural choice for detecting spatial relationships among geologically related data and helps users comprehend phenomena.

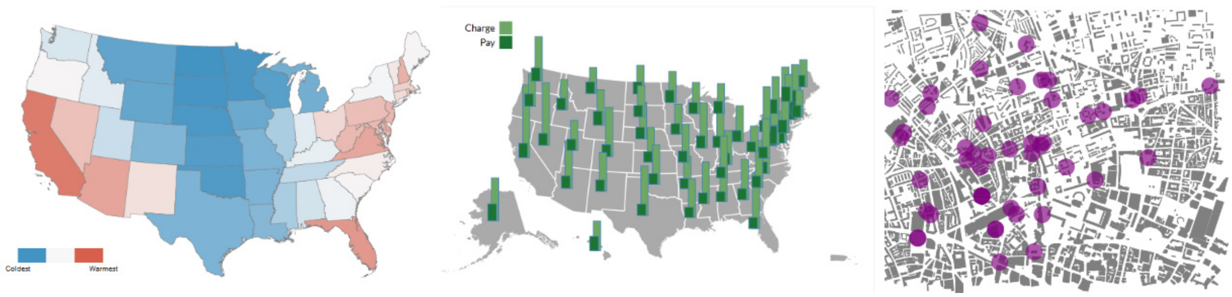

Figure 3: Possible Geospatial Visualization Methods[22]

Geospatial visualization tools provide users with the ability to visualize spatial relationships within large data sets. Most PLM data has a geographic location such as plant locations across the world, distributions of buyer values and seller costs, and sales territories. Oracle Business Intelligence Suite offers numerous geospatial visualization methods for PLM data. They deliver deeper analytical insights through thematic map visualization and add bar charts, graphs, and detailed reports to the map view. Anything that contains a physical location such as revenue, billed quantity, and shipped amount can be leveraged by geospatial visualization tools.

Multidimensional visualization

Multidimensional visualization is developed to deal with data of more than two attributes. The common visualization techniques for multidimensional visualization are bar chart, pie chart, parallel coordinate plot, scatter plot matrix, heat map and tree map. For example, each vertical axis in parallel coordinates corresponds to each of the dimensions, and its value represents the dimensional data (Figure 4, left). All the individual data elements are color coded and connected by lines depending on different characteristics. A scatter plot matrix is widely used for pairwise relationships. It shows ordered groupings of dimensions along vertical and horizontal axes (Figure 4, right).

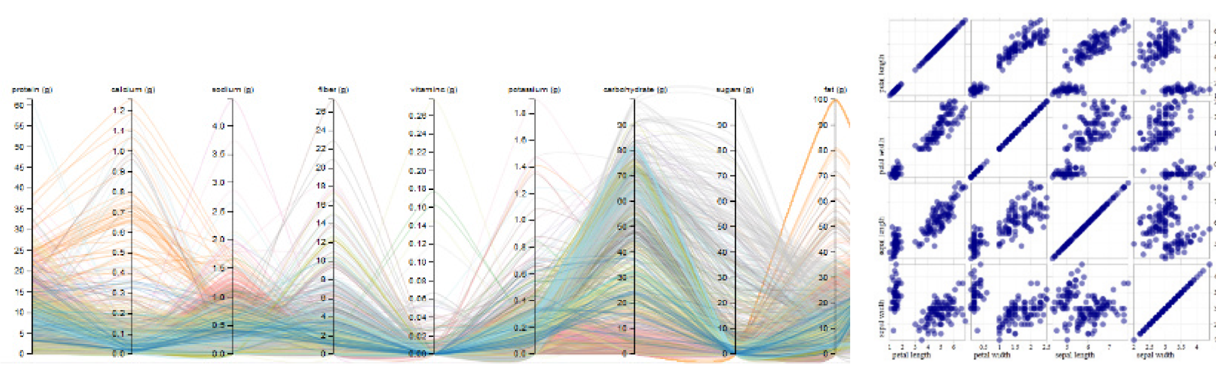

Figure 4: Possible Multidimensional Visualization Methods[22]

Multidimensional data is everywhere in PLM. A multilevel product can consist of multiple subassemblies and parts[1]. Many PLM applications use BOM to show a detailed list of data attributes. Most often the BOM is stored as a spreadsheet. It will be very hard to read if there are many parts in the BOM. Although the data can be put into a relational database to query limited information, it requires special training to use a database, and it costs more time and money. Thus multidimensional visualization techniques are suited to show the higher dimensions of BOM data. They can display the relationships among sales data, material types, warranty claims, and geometric information about parts. Moreover, through interactive filtering, zooming, and brushing, the visualization can provide more-focused analyses and touch different functions across the product lifecycle.

Obviously, information visualization provides various perspectives on PLM data through multiple visualization modules. It would enable any PLM user, including participants from design, engineering, manufacturing, and marketing, to interpret and share PLM data. The barriers of "islands of data" can be broken down, and different participants in the lifecycle can demonstrate their expertise and also inspire others with good problem-solving ideas.

A Case Study

This paper demonstrates the idea by a case study of developing an Internet-based information visualization system to help users interpret, manage, and analyze PLM data. Users can gain insight into the data via an overview of relationship, zooming, connecting and navigating. The representative data is collected from the Shuang Ma 9053 RC Helicopter (Figure 5).

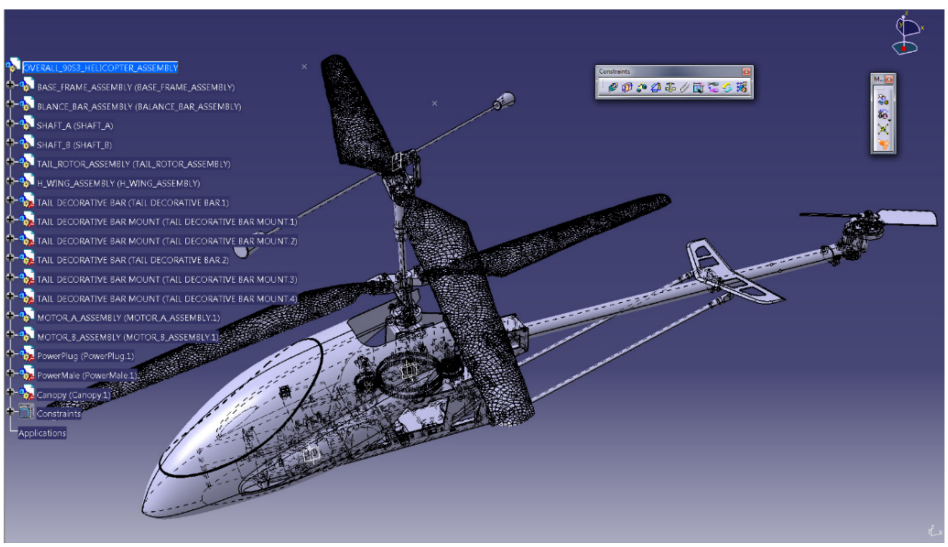

Figure 5: The Shuang Ma 9053 RC Helicopter 3D Model

Framework of the Web-based product data visualization system

The framework for the Web-based visualization system is divided into three different layers according to Model-View-Controller (MVC) design[23]. The project constructed the 3D geometric model via CATIA and then extracted all the metadata for each assembly from CATIA to create a Bill of Material (BOM). The data include but are not limited to part number, file name, assembly level, volume, mass and link to different parts or components. Such data comprise the model layer. The controlling layer is responsible for service requests and query-task execution. With requests, such as finding a spare part or searching a subtree, the server can extract and display

PLM data. The view layer aims to provide rich interactive visualization interfaces for different roles of PLM users. Different users may be interested in different perspectives of the data. Industrial designers may be interested in the look and feel of the product, which is the 3D mode visualization. Some engineers may be interested in finding the weakest link in the product. Others may be interested in seeing the cost of parts in the product and looking for ways to reduce costs. Effectively combining visualization tools, the system can lead to better product understanding and help users make accurate decisions.

Product data visualization

The model was built according to the Shuang Ma 9053 RC helicopter specifications (Figure 5). Researchers implement three different visualization graphs for RC helicopter data with the D3js library (http://www.d3js.org). The platform enables users to click an individual node to see its 3D form and metadata structure in the webpage based on HTML 5's WebGL technologies and three.js (http://www.threejs.org).

Figure 6: A Tree Graph to Visualize Hierarchy Data and Make Trade-offs

Visualizing general hierarchy of product data: The hierarchical tree visualization helps users see the product hierarchy, determine which parts will be required when assembling, and make it easier to find part replacements. The tree graph visualization tool enables designers to view a node's "parent" and "sibling" (Figure 6). We provide a radial view with circular wedges to show the parent-child relationships. The root is in the center with different layers growing around it. The depth of each node refers to the path to its root and the link length represents the strength of connection between nodes. Currently such trees must be widely adopted to visualize the Bill of Material (BOM) data of a product. There is a strong need in PLM to understand the connection between entities and manipulate sub-trees in the structure. Such analysis requires a combination of different visualization techniques. This tree graph uses the connection technique to help user explore hierarchical data from multiple views. By clicking on each node, users will navigate to a webpage showing the node's corresponding part tree and related metadata information, making it easier to gain insight into sub-assembly data. Through connecting and navigating, users can interact with the tree structure and clarify the relationships in the data.

Making appropriate trade-offs between attributes: Engineering designers are always seeking appropriate solutions to product development. The nodes and edges in a tree can be utilized to display many attributes of the represented entity. The color of each node encodes the materials (Figure 6). Orange is assigned to multiple materials, gray to aluminum, blue to plastic and red to unavailable materials. Node size is related to part weight. Designers can make appropriate trade-offs between material, volume, and weight. Knowing the weight and bounding size of each part can help designers find the heaviest parts and stay within certain weight constraints. Other than color and size, a node can also use different shapes and boundaries to represent more attributes, for example, costs and lifespan. Within a limited display space, a static tree graph cannot accommodate extreme complex products that contain millions of parts and many hierarchical layers, for example, the Boeing 777, which has more than 6,000,000 parts. One direct solution is to create a collapsible tree graph and brings in interaction. By default, it only displays a certain level of the hierarchy without expanding to the end leaves. The user can interact with the graph to expand or collapse branches (Figure 7) by clicking on nodes. Also some visualization techniques have been proposed to visualize large trees, such as a botanical tree to visualize large information sets[24], a focus+context (fisheye) technique for displaying huge hierarchical structures[25] and SpaceTree to support aggregation and navigation in the large hierarchy with screen-optimized dynamic layout of nodes[26].

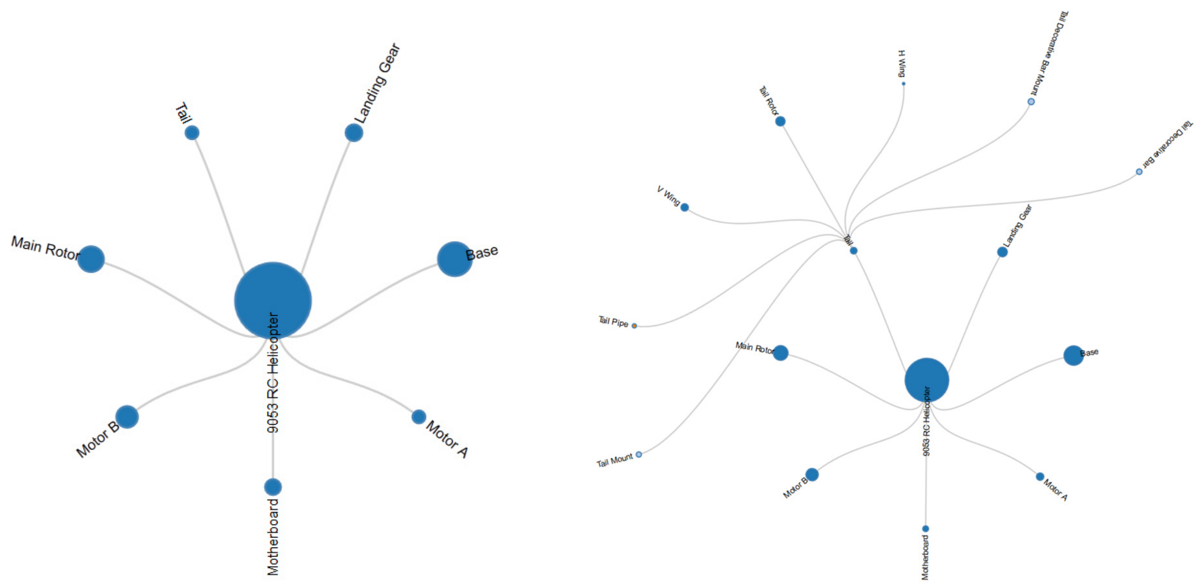

Figure 7: A Collapsible Tree Graph to Expand or Collapse Branches

A zoomable sunburst partition is also created to demonstrate the quantity percentage of the attributes of parts (e.g., weight and costs). It uses radial space-filling visualization with labels aligned with each arc's angle span to show part names. The color of each represents the material, and the proportional size of the node encodes the relative cost (or weight) of the material (Figure 8). This visualization technique also supports mouse hovering and clicking interaction. By hovering and clicking each node, users can smoothly zoom in and zoom out of the hierarchy. This simple interaction approach allows users to highlight certain items among thousands of elements. Thus, Designers can quickly see how much it would cost to use the material and thus have a better focus on improving the product, for example, spending more time to redesign to most expensive (or to the heaviest) parts to reduce the overall cost of the product.

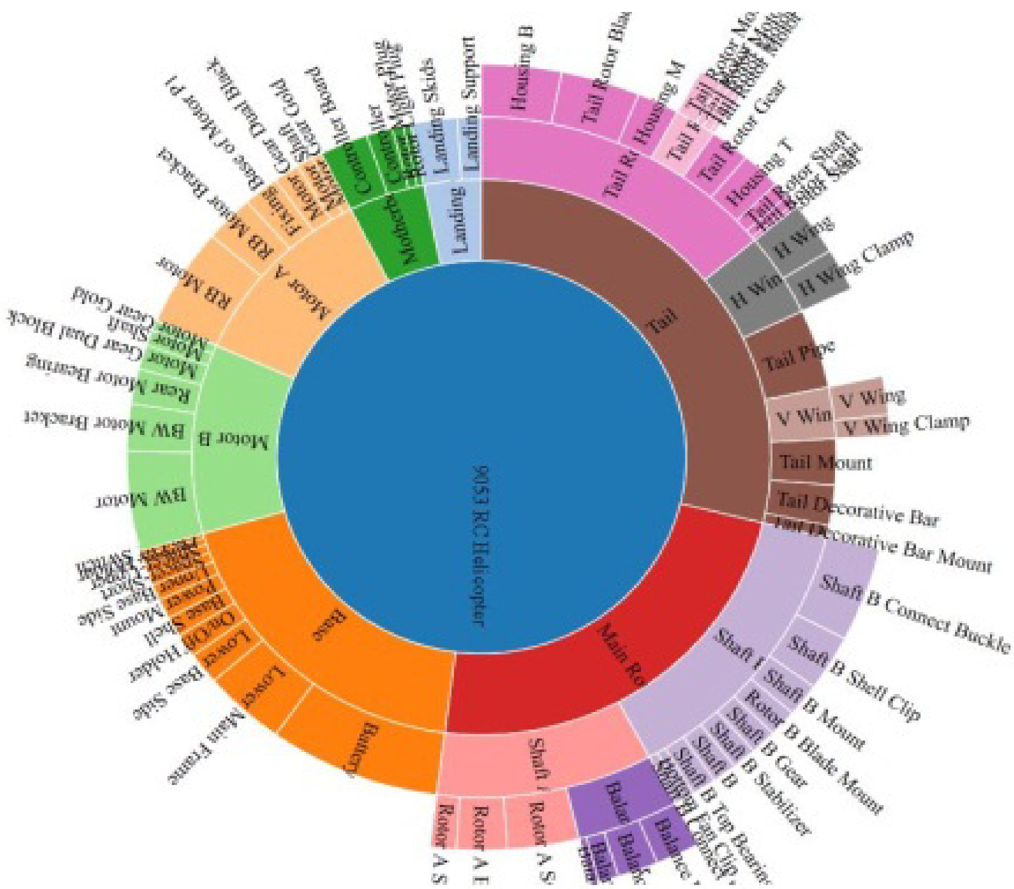

Figure 8: A Zoomable Sunburst to Visualize Hierarchy Data and Relationships

Finding the strength of connection between components: Based on the helicopter BOM data, we created an L-matrix diagram to display the network relationship among parts. The strength of connection indicates the relationship between individual components. An example of a vulnerable connection would be the connection between the battery and the battery holder. An example of a strong connection would be the concentric constraint between the blade mount and the shaft of the Shaft B Subassembly. We put each part number into the corresponding row and column of cells in a spreadsheet. The color squares represent the strength of the connection between the component in the x-axis and the other one in the corresponding y-axis. There is no sense in comparing a part to itself so the light blue squares mean that there is no correlation between them. Dark blue encodes a weak connection, and orange designates a strong connection (Figure 9). The closer the connection assignment is to the light blue diagonal, the closer the components are in the actual 3D model. For maintenance, repair and operations (MRO) of aircraft, the visual analytic tool will help them quickly find problems and make the right decision. The user can also see the importance of one part in terms of connectivity by looking at color squares in one row (or column). The more squares, the more connections the part is linked to other parts. Therefore, this part may merit closer attention for maintenance because its failure may cause the failure of other parts.

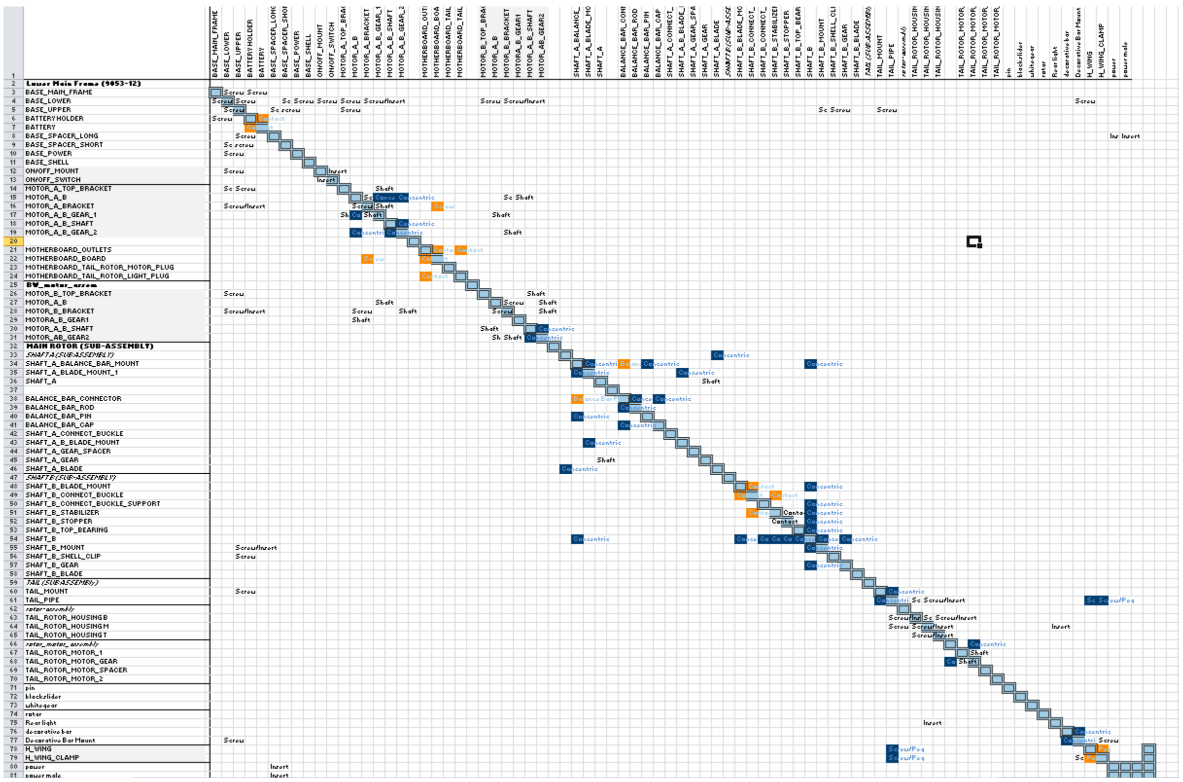

Figure 9: A Matrix Diagram to Visualize Physical Connections Among Assemblies

Mapping product structure into a 3D geometric model: The node tree graph conveys more-abstract information to users, and the 3D model shows more-realistic information. With HTML 5 and WebGL technology, the platform integrated the node tree and 3D models on the Web page (Figure 10). If users click a node, it will link to the Web page with an integration of a subtree graph, a table of product data, and a simplified part model. The subtree graph is on the top right of the following figure and it contains hierarchical information of the helicopter base. Detailed subassembly information is displayed on the top left of the following figure and users can view the metadata such as part number, material and assembly level of the base. The corresponding 3D base model is at the bottom of the figure. Users can rotate the model for 360 degree view with a mouse. With an integration of all these visualizations, customers will have a better understanding of the product development information, and various departments will have a more-effective communication to share ideas and thoughts for innovation and evaluation.

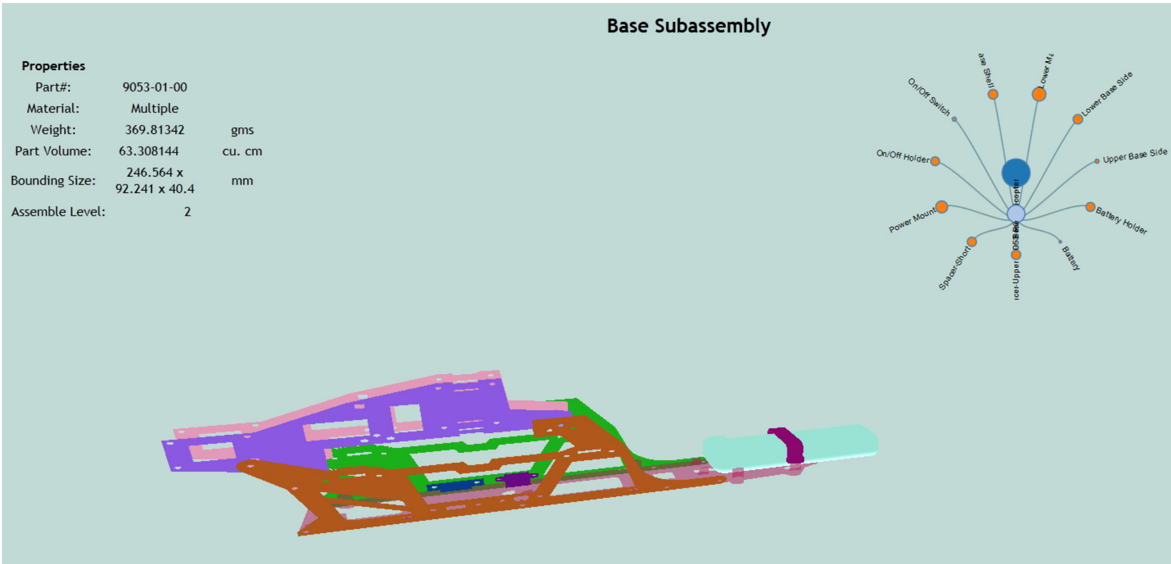

Figure 10: Web-based Product Visualization Platform for Helicopter

Conclusion and future work

We demonstrated using information visualization technologies to communicate product abstract data with vivid 3D models. This research is not intended to replace 3D models. A 3D geometric model is by far the most intuitive and popular way to provide a realistic representation of a product in context. It also delivers better insight into surface patterns of objects and enables designers to inspect for errors that might occur in the drawing process. In traditional PLM environment, designers are always working with 3D solid data, and it is not easier for them to deeply visualize hierarchical structure of product data or gain insights into important 2D information. Possible visualization techniques such as structural visualization, temporal visualization, geospatial visualization, 3D model visualization, and multidimensional visualization allow users to interactively explore large PLM data resources. Moreover, combining 2D graph data with 3D solid model will provide a faster and more intuitive way to make decisions.

While designing a visualization graph, for given type of data, there may exist several different visualization algorithms that the designer can choose. Also the choice of color, layout details, and graph elements vary greatly depending upon the nature of the data, the main purpose of product data communication, and the readers’ acceptance of different visualization methods. In this paper, we have presented our first approach of using information visualization to communicate product data. We can see that there is still a lot of work to be done in this area. The data in the use cases we gathered are directly from the 3D model of the RC helicopter. Figure 6 and Figure 8 are created based upon the same data, but displayed in totally different ways. The L-matrix diagram (Figure 9) can also be shown in different ways, such as the circular layout for networks (the third image from left in Figure 1). Compared with the circular layout, the L-matrix is wasting space, but is well organized and easier for users to read and understand the connections among different parts.

The ultimate goal of the research is to bring the power of visual analytic tools to mainstream PLM applications, e.g., Dassault's ENOVIA[27] or Siemens' Teamcenter[5]. This will not only benefit engineering design and make economic sense, but it will also increase customer satisfaction. In the future, research will conduct user evaluations with internal controlled experiments and external usability surveys. Researchers will also iteratively conduct cycles of design and evaluation.

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Bibliography

1. J. Stark, *Product lifecycle management: 21st century paradigm for product realisation*. Springer, 2011.
2. K. A. Cook and J. J. Thomas, *Illuminating the Path: The Research and Development Agenda for Visual Analytics*. 2005.
3. PTC, "Introduction to Creo View MCAD 2.0." [Online]. Available: http://dseserve.com/PTC/T3918_Exc_Guide/#/2/. [Accessed: 24-Dec-2013].
4. Siemens, "HD3D Visual Reporting." [Online]. Available: http://www.plm.automation.siemens.com/en_us/products/nx/for-design/visual-analytics/reporting.shtml. [Accessed: 24-Dec-2013].
5. Siemens, "Teamcenter: Siemens PLM Software." [Online]. Available: http://www.plm.automation.siemens.com/en_us/products/teamcenter/. [Accessed: 08-Oct-2012].
6. A. Pleuss and G. Botterweck, "Visualization of variability and configuration options," *International Journal on Software Tools for Technology Transfer (STTT)*, pp. 1–14, 2012.
7. W. Berger, H. Piringer, P. Filzmoser, and E. Gröller, "Uncertainty-Aware exploration of continuous parameter spaces using multivariate prediction," in *Computer Graphics Forum*, vol. 30, pp. 911–920, 2011.
8. K. Matkovic, M. Đuras, D. Gracanin, R. Splechtna, B. Stehno and H. Hauser, "Interactive visual analysis in the concept stage of a hybrid-vehicle design," in *EuroVis Workshop on Visual Analytics*, 2013, pp. 61–65.
9. S. Nakamura, Y. Kondo, K. Matsubae, K. Nakajima, and T. Nagasaka, "UPIOM: a new tool of MFA and its application to the flow of iron and steel associated with car production," *Environ. Sci. Technol.*, vol. 45, no. 3, pp. 1114–1120, Feb. 2011.
10. H. Wang, G. Zhao, W. Wang, and C. Chen, "The design and implementation of the platform of interactive information visualization on aircraft product development," in *System Science, Engineering Design and Manufacturing Informatization (ICSEM), 2012 3rd International Conference (IEEE)*, 2012, vol. 1, pp. 180-184.
11. Y. Li, R. Yan, and J. Jian, "A semantics-based approach for collaborative aircraft tooling design. Advanced Engineering Informatics," *Advanced Engineering Informatics*, vol.24, no. 2, pp. 149–158, 2010.
12. M. R. Cutkosky, R. S. Engelmore, R. E. Fikes, M. R. Genesereth, T. R. Gruber, W. S. Mark, J. M. Tenenbaum, and J. C. Weber, "PACT: An experiment in integrating concurrent engineering systems," *Computer*, vol. 26, no. 1, pp. 28–37, 1993.
13. P. Trott, *Innovation management and new product development*. Prentice Hall, 2008.
14. H. L. Broberg and others, "Internet-based monitoring and controls for HVAC applications," *Industry Applications Magazine, IEEE*, vol. 8, no. 1, pp. 49–54, 2002.
15. P. Siltanen, and S. Valli, "Web-based 3D Mediated Communication in Manufacturing Industry," in *Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment*, pp. 1181-1192, 2013.

16. A. Malik, R. Maciejewski, B. Maule, and D. S. Ebert, “A visual analytics process for maritime resource allocation and risk assessment,” in *Visual Analytics Science and Technology (VAST), 2011 IEEE Conference on*, 2011, pp. 221–230.
17. X. Wang, W. Dou, S. E. Chen, W. Ribarsky, and R. Chang, “An interactive visual analytics system for bridge management,” in *Computer Graphics Forum*, 2010, vol. 29, pp. 1033–1042.
18. C. P. Wong, K. Schneider, P. Mackey, H. Foote, G. Chin, R. Guttromson and J. Thomas, “A novel visualization technique for electric power grid analytics,” *Visualization and Computer Graphics, IEEE Transactions on*, vol. 15, no. 3, pp. 410-423, 2009.
19. J. Stasko, C. Görg, and Z. Liu, “Jigsaw: supporting investigative analysis through interactive visualization,” *Information visualization*, vol. 7, no. 2, pp. 118–132, 2008.
20. N. Kadivar, V. Chen, D. Dunsmuir, E. Lee, C. Qian, J. Dill, C. Shaw, and R. Woodbury, “Capturing and supporting the analysis process,” in *Visual Analytics Science and Technology, 2009. VAST 2009, IEEE Symposium on*, 2009, pp. 131–138.
21. B. Shneiderman, “The eyes have it: A task by data type taxonomy for information visualizations,” in *Visual Languages, 1996. Proceedings, IEEE Symposium on*, 1996, pp. 363–343.
22. d3js.org, “Data-Driven Documents.” [Online]. Available: http://www.d3js.org. [Accessed: 4-Jan-2014].
23. E. G. Krasner and T. S. Pope, “A description of the model-view-controller user interface paradigm in the smalltalk-80 system,” *Journal of Object Oriented Programming*, vol. 1, no. 3, pp. 26–49, 1988.
24. E. Kleiberg, H. Van De Wetering, and J. J. Van Wijk, “Botanical visualization of huge hierarchies,” *In Information Visualization, IEEE Symposium on,* 2001, pp. 87-87. IEEE Computer Society.
25. J. Lamping, R. Rao, and P. Pirolli, “A focus+ context technique based on hyperbolic geometry for visualizing large hierarchies,” *In Proceedings of the SIGCHI conference on Human factors in computing system*s, 1995, pp. 401-408. ACM Press/Addison-Wesley Publishing Co..
26. N. Elmqvist and D. J. Fekete, “Hierarchical aggregation for information visualization: Overview, techniques, and design guidelines,” *Visualization and Computer Graphics, IEEE Transactions on,* vol. 16, no. 3, pp. 439-454, 2010.
27. Dassault, “ENOVIA - Collaborative Innovation Application - Dassault Systèmes - Dassault Systèmes.” [Online]. Available: http://www.3ds.com/products/enovia. [Accessed: 08-Oct-2012].