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A novel product representation to highlight cross-assembly dependencies and product robustness

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Abstract

Manufacturing industry has traditionally used Bill of Materials (BOMs) and Product Lifecycle Management (PLM) tools to track components and sub-assemblies within a product. These apply a hierarchical structure to product assemblies and sub-assemblies. Impacts of change to one or more components can easily be traced throughout the assembly tree; however, changes impacting another component not directly or explicitly connected to the first are not considered. Here the authors present the novel Kendrick Reticulated Ontology Model (KROM), a mesh component network to highlight cross-assembly dependencies. N^{th}–order connections are considered through user inputted links between otherwise unconnected components. Unexpected emergent behaviours can therefore be anticipated. Network analysis was applied to the resulting graph, quantifying the design's robustness though centrality measures. Considering both product components and assembly associated tooling and jigging demonstrates the true propagating impact of design change. It is shown that core component connectedness order is changed when tooling becomes part of the network. This is particularly significant when considering the regular omission of tooling in BOMs. Here, a disconnection between Design Engineering and Production Engineering after design finalisation has been determined and a solution presented.

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Keywords: design change; network analysis; ontologies; PLM

1. Introduction

Engineering progress allows increasingly complex designs to be manufactured in line with consumer need. These products combine several disciplines of engineering, typically software, electrical and mechanical. Design of new products is an engaging task, but it is subsequent updates that often cause issues [1]. Individual components must be upgraded to meet new demands, add flexibility, lower cost or address robustness. Changing one component commonly has a knock-on effect, be it direct mating constraints or less obvious connections. Product Lifecycle Management (PLM) and Product Data Management (PDM) tools aid engineers; however these typically depict the system as a sub-assembly hierarchical tree. This is suitable for management and component identification, but will not allow cross-assembly connections to be considered. For changes to be correctly managed, potential synergy between parts must be identified, allowing emergent properties to be identified at an early stage.

2. Current State

2.1. Industrial Context

21st century manufacturing industry prides itself on ability to design, model and track components and sub-assemblies of complex products. Extensive Computer Aided Design (CAD) and PLM systems allow complex electro-mechanical products to be successfully manufactured in high volumes, with the ability to track design changes.

Many companies endeavour to manufacture parts in-house, reducing cost, ensuring quality, alleviating supply chain dependency and maintaining intellectual property (IP). Through this method all aspects of product design and

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innovation are controlled within the company. Those with the ability to internally manufacture parts often have manufacturing centres geographically separate to design offices. It is common to design in one country and manufacture and assemble in another due to labour costs and experience. The continuous improvement ethos the engineering markets demand ensures design changes are constantly planned for existing products and cut-in to current designs.

To line with this, linked CAD/PLM systems [2] [3], that allow the user to create a part and identify it with a unique part number, are used. Parts are then sub-assembled and assigned an assembly number. Sub-assemblies are amalgamated into higher-level assemblies until final assembly is reached. Connections used are solely geometric.

When a part needs to be interrogated it can be accessed through a search function and assemblies where the part is used can be highlighted. This hierarchical view allows users to quickly identify where parts fit, but the impact outside of the sub-assembly and direct parent assembly is not instantly apparent.

This limitation is exemplified by a designer wanting to alter the length and end profile of a support leg. This change requires a base to be changed and extension of the cable running down the leg. If the support leg is interrogated with a 'where used' command only the leg assembly will be highlighted. If there is no physical link between this part and the base or cable, a designer will only assimilate wider effects of the design change with tacit knowledge of the system. Links may not be obvious so one design alteration can produce many unanticipated consequences.

In addition, if there is no unified database of production jigging, tooling and component parts, consequences of design changes are often missed. Corporate production, design and assembly database linking varies, but typically these are considered separate entities owned by one division. Equally jigging is not typically modelled in the CAD systems, so geometric relations are not explicitly recorded between parts and tooling.

2.2. Justification

This research addresses an essential issue – design change tracking implications. Moreover it serves as an approach to link product to process, closing the communication loop between production and design. Emergent behaviors within systems, caused by successive change of multiple parts, are shown to be predictable at design level by a novel system, termed the Kendrick Reticulated Ontology Model (KROM) by the authors.

Mihm and Loch [4] describe the knock-on effect of design change as 'problem-solving oscillations'. They note that complex systems can be described as components belonging to different domains and that lack of communication between these domains leads to errors rippling from a change of one module to unintentionally affect another. A final design can only be reached once methods are implemented to rapidly locate ripple effects. They propose improved communication methods and CAD based spatial dependencies to communicate a component design change to 'a few critical other components'. However, the ideal solution suggested is still a component hierarchy.

Ulrich [5] proposes a mapping network of functional elements to physical components in order to aid initial design and inform design change; whilst Lu *et al* [6] use abductive reasoning to highlight design proposal constraints and aid designers. Both show a requirement for KROM.

2.3. Available Tools and Systems

As previously mentioned CAD, PLM, PDM and BOM systems are commonplace in the manufacturing sector. These tools are essential in the management of product design and production. Mathers [7] stated that a well-defined BOM should incorporate a wide range of information including: product definition, manufacturing instructions, engineering change control, service part support, warranty policy, order entry, costing and pricing.

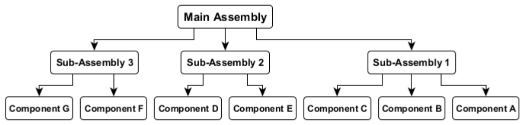
BOM can be automatically generated from PLM, but at present only contains part name, quantity, cost and stock location. The BOM is produced from a single product line; however the new product can form a family of products. Whilst the functionality of product family tracking is available in the existing PLM software it is not currently utilized by many companies. Various solutions on how to manage product families have been commercialized from the literature [8] [9], such as the use of a graph theoretic (minimum common supergraph) approach to find the 'common denominator' for a series of product variants.

3. Implemented Solution

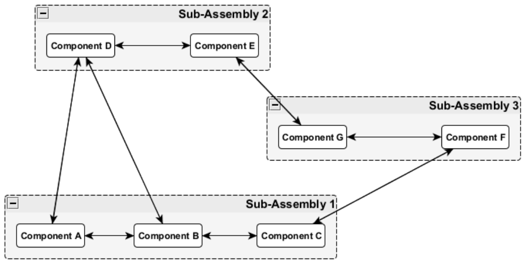
In order to link product to process and highlight design change impact, representations of system connections have been addressed. Instead of the current hierarchical assembly tree representation, a reticulated network of cross-dependencies, KROM, was created, as shown in Figure 1. This approach allows cross-assembly links to be included so dependencies that would otherwise be overlooked are considered.

This will allow design interrogation, enabling designers to run speculative scenarios to model potential design changes. This effectively creates a tool for Lutter's *et al* [10] 'What-if' design synthesis model, where the designer is presented handles to adjust parameters of components and trace the effects.

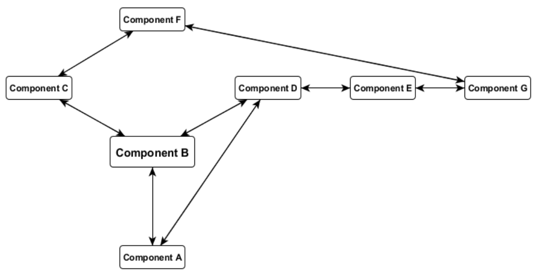
This paper demonstrates a framework for KROM, both for a new product, and retrospectively for an existing product line. Examples were created using the yED software [11] which allows graphical networks to be visualised and rearanged using the yED built-in layout algorithms. Graphs were saved in Graph Modeling Language (GML) format, and imported and parsed into MATLAB, through which Network Analysis was implemented using a custom script.



(a) Hierarchical Representation



(b) Sub-Assembly Grouped Reticulation



(c) Component Cross-Dependency Network

Figure 1: Reordering a component network from a hierarchical view to a reticulated view, to make tacit, cross-assembly links visible

4. Introduction to Connectedness

Dividing a product into constituent components and tooling, allows a user to conduct design analysis. Network analysis can be used to measure connectivity and robustness; *centrality*, the measure of the distance of each node in relation to all other nodes, can be obtained individually or as a whole graph aggregated value. There are three main centrality measurement types:

Degree Distribution, C_{Di} – states the number of edges (connections) a particular node has. [13]

$$C_{D_i} := \frac{\text{node degree}}{\text{total edges}} \quad (1)$$

Closeness Coefficient, C_{Ci} – measures how close one node is to every other. This produces a fraction, between zero and one, equal to the number of reachable nodes divided by the sum of the shortest routes to those nodes. A value of one shows direct connectivity to every other node. [13]

$$C_{C_i} := \frac{n}{\sum_{j \in N/i} d(i,j)} \quad (2)$$

Where i is the starting node, j is the finishing node, n is number of reachable nodes, N/i is sum of all reachable nodes (excluding i) and d(i,j) is shortest path length.

Betweenness Coefficient, C_{Bi} –measures the frequency of a node lying on a shortest path. The output between zero and one, one indicating the node lies on every shortest path in the graph. [14]

$$C_{B_i} := \sum_{j,k \in N/i} \frac{\sigma_{j,k}}{\gamma_{j,k}(i)} \quad (3)$$

Where $\sigma_{j,k}$ is total number of shortest paths from j to k, $\gamma_{j,k}(i)$ is number of shortest paths from j to k bisecting i and N/i is the set of all nodes reachable from i (excluding i).

These centrality measures allow design analysis: when the resulting component graph is highly connected, a design change or component failure will have a higher impact on the product than if the design had more redundancy. Additionally, individual components can be critically ranked based on connection number and centrality. This can influence product level design changes, and inform resource allocation if highly connected components require alteration.

4.1. Centrality Examples

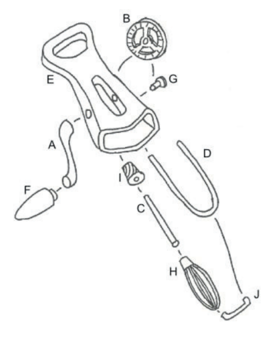
The following extremes exemplify centrality output of archetypal product's KROM graphs. The evenly connected mesh product, a handheld whisk, has an even spread of component connections; whereas the star product, an office chair, is centrally connected through a central hub (Figure 2).

Figure 3(a) shows the degree distribution for both these products. Although dependant on the number of overall connections, a mesh product typically has a higher proportion of nodes with similar degree. Here, most of the nodes have a degree of three. A star product will have a degree split, with most components having a lower degree (in this case one or two) and a single node having a much higher degree (in this case seven). In both cases there will be no zeroth degree as the graphs are completely connected.

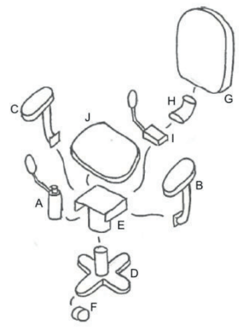
Figure 3(b) shows the closeness centrality of both products. A mesh product will have a more even spread of closeness coefficients, as most components are relatively close to one another. A star graph will have a spike of closeness for the central node.

Figure 3(c) shows the betweenness centrality of the products. The mesh product will have a betweeness value for most components as they lie on the shortest paths. A star product will have a spike of betweenness for the central node as this almost certainly lies on the shortest path for most components.

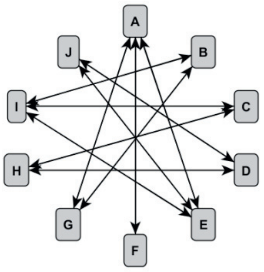
Both designs have advantages and may be preferred under different design requirements. A mesh product has numerous connections between components so is more prone to design change impact if one of the components is changed; it is



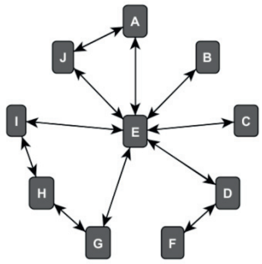
(ai) Mesh product - a hand whisk



(bi) Star product - an office chair



(aii) Hand whisk KROM



(bii) Office chair KROM

Figure 2 – Example KROMs for: (a) a mesh and (b) a star product

inherently less reliant on a singular component. A star component will have many peripheral components which can be changed with fewer ramifications; however these designs focus solely around a few core components, which if changed will require considerable planning to accommodate the resulting knock-on effect.

5. Case Study

5.1. Case Study Introduction

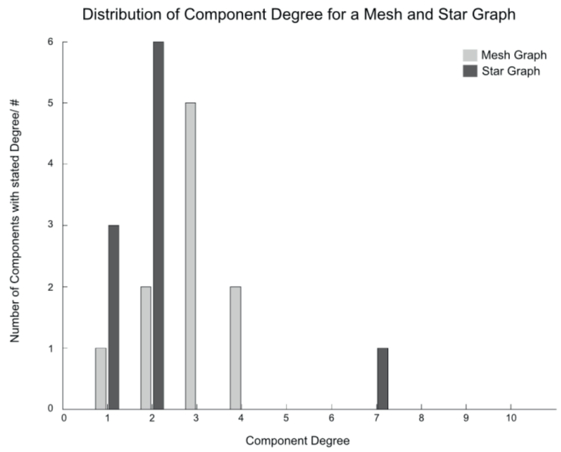
In order to trial this approach a product line was selected at a medium-sized SME. The product is electro-mechanical and consists of over 100 components. This product had a KROM built from first principles, using data available on the existing PLM system and interviews and workshops with Engineers working in the design and production teams.

5.2. Stakeholder Engagement

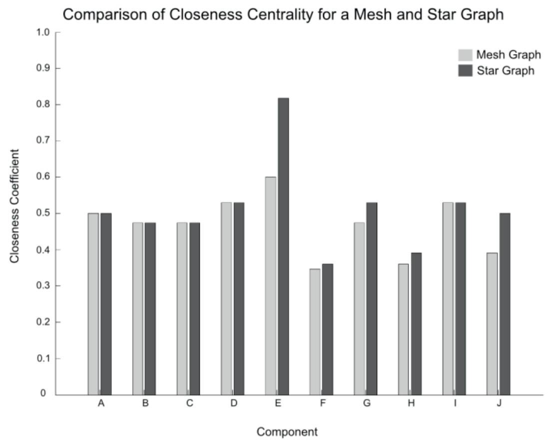
In order to populate the design graph the tacit knowledge of the stakeholders is required. Both design and production team members were consulted. In knowledge capture a key ontology between all parties must be established [12]. Utilizing the existing component database in the PLM system, a graph was populated using cross-component connections.

5.3. Assumptions

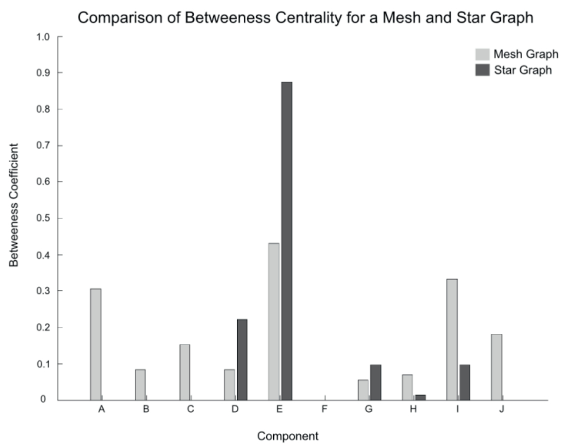
In order to maintain a sense of scale only higher level components were used. Part numbers of external origin were



(a) Degree Distribution



(b) Closeness Centrality



(c) Betweeness Centrality

Figure 3 – Archetypal Connectivity plots for Mesh and Star Products

not included. Typically, externally procured parts, e.g. washers, bolts and sensors are of standard sizes. Their exclusion made the size of the graph realizable as proof of concept and any design change would have to be planned around these standard sizes.

Secondly, electronic components are considered to be black boxes. Populated PCB boards were considered as a whole and an electrical component level of detail was not included.

6. Results and Network Analysis

6.1. Resulting Tool Diagrams

Having populated the networks, reticulated depiction of product components can be viewed as closed or open, where the user can see individual parameter connections to other impacted components.

Typical PLM systems only contain components that are directly used in the assembly of the product. Thus any decisions regarding component design change are often made without fully considering the current tooling. Without a direct link between components and tooling, the impact of design alteration on one component is not seen on another component whose only link is through a tooling intermediary. Figure 4 shows the network and associated connections when tooling and jigging is placed in addition to the components. When using the tool a node can be selected and centred. It then has the order of connections colour coded and arranged radially, allowing users to quickly determine how a change of one component will proliferate through the design (Figure 5).

6.2. Design Analysis Utilising Component Connectedness

Using network analysis tools, the product can be split into highly and less connected components. The degree distribution, closeness coefficient and betweenness coefficient for a particular electro-mechanical product consisting of over a hundred higher level components was ascertained. This allows users to rank the connectedness of individual components. If a component is shown to be highly connected a minor design change can be forgone, or if the change is necessary more resource can be attributed to minimize the impact of the change.

In the case study six components proved to be highly connected and were in the top eight of all three connectedness measures. This was more obvious in the degree distribution which directly relates to how many components each part is connected to. The rapid drop off of the component connectedness indicates that whilst these core half dozen components are fundamental to the design, the vast majority of other components are only minimally connected and lie on the fringe of the design. This implies that the majority of the components can be changed without too much implication; however if one of the core components needs to be changed a more considered approach would be required.

This observation is mirrored by the shape of the betweenness graph – in which only a few core components lie on the shortest path between other components, whilst most

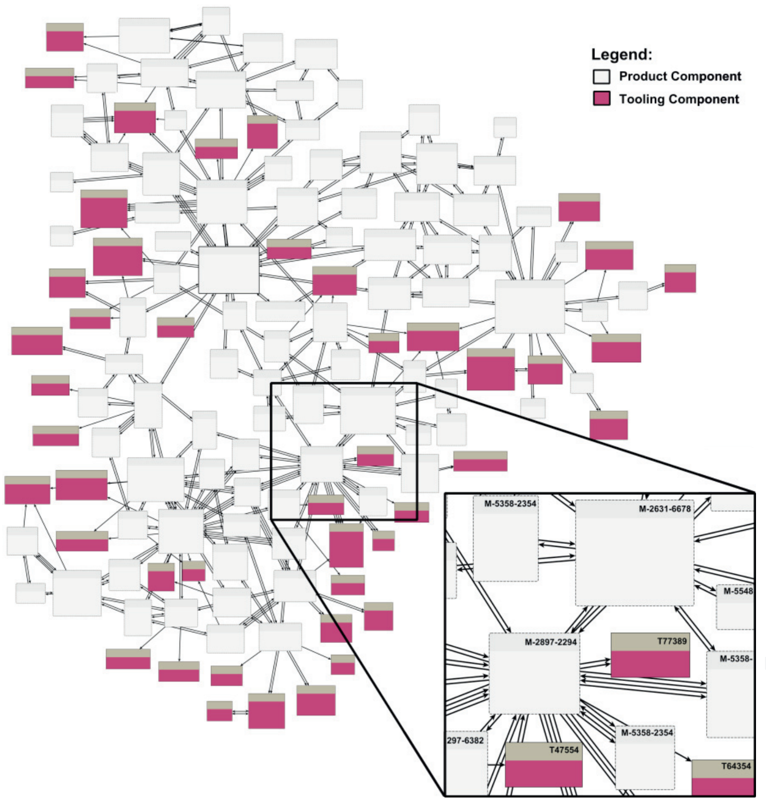


Figure 4: KROM depiction of case study product showing connectivity of product (grey) and tooling (purple) components. Inset illustrating zoomed section showing multiple connections between different component types

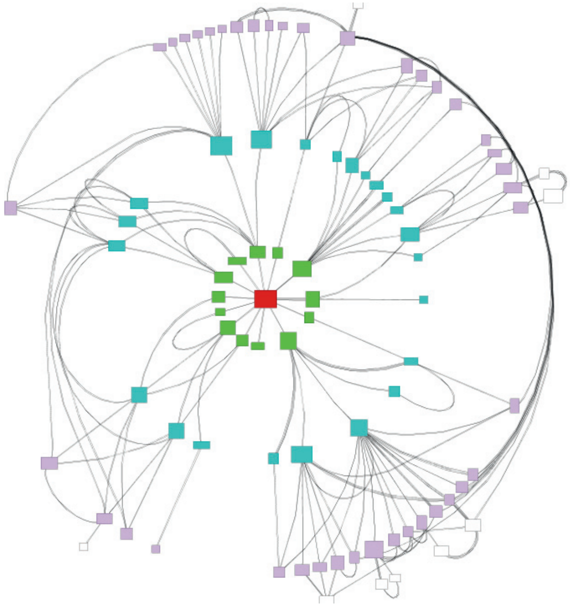


Figure 5 - Radial representation of the complete graph, with colour showing the order of connection to the centrally selected component (Red). 1st Order Connection: Green, 2nd Order: Blue, 3rd Order: Lilac, Higher Order: White

others lie on the fringes and are not on critical paths.

Due to this star arrangement for the product the closeness of components is quite consistent, as most components can reach other components through a minimal number of intermediate components.

6.3. Impact of Including Tooling

Including tooling adds extra nodes separate from main component nodes as they create unidirectional links. Tooling changes the connectedness order of the system, as indicated in Figure 6. Components that were less connected become more sensitive to design change. This highlights a crucial issue often overlooked in engineering – the assembly implication of design changes. By linking jigging to actual product models, design changes can be linked to production requirements. This informs both designers and production staff, who may be separated geographically and unable to share unrecorded tacit knowledge easily.

6.4. Concept Expansion

Whilst the model completed in the course of the research proves the benefits of employing a reticulated ontological approach to product data capture, it focuses mainly on n-th order geometric links and tooling for assembly. When stakeholders were considered it was clear that this approach would benefit from recording other classes of connection.

Project Managers have highlighted that using this tool to record ordering availability and timeframe would be invaluable when substituting one product level design change for a later iteration. In this fashion it would be obvious to see where bottlenecks occur in the transition of one product's modification level to another.

Manufacturing staff have commented on how including manufacturing processes would also bring new insight as the order of these processes, associated tolerances and aesthetic finish have an impact on other parts in the system. Moreover energy used and cost per part could be analysed over the entire model.

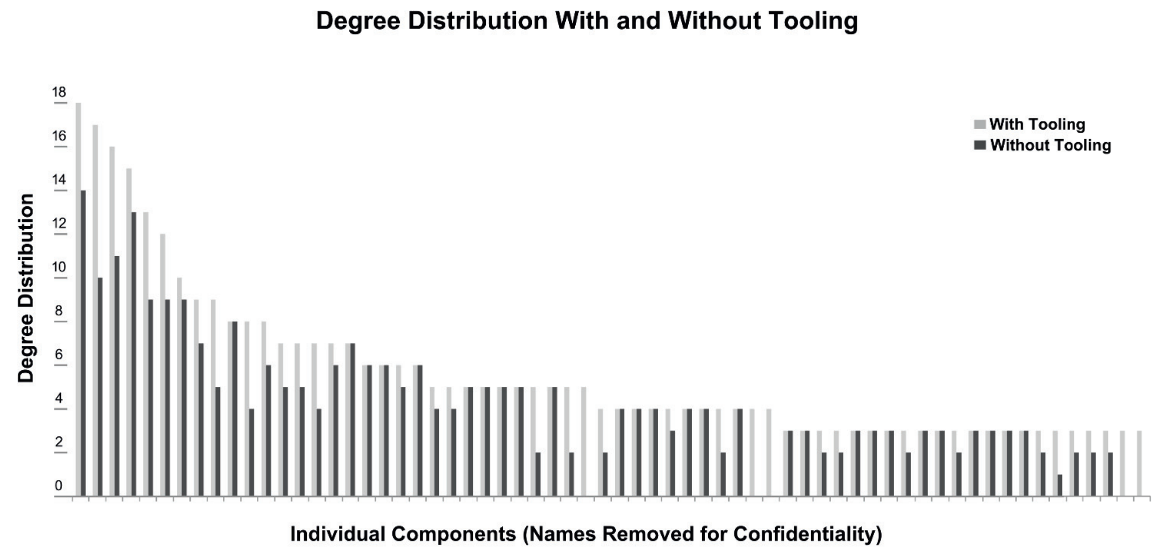


Figure 6: Degree Distribution of components in graph including tooling, and graph without tooling. As shown the order of the components changes when tooling components are included and when they are not. This indicates the robustness sensitivity of a product to its manufacturing elements (jigs, tooling and fixtures).

6.5. Case Study Feedback

Upon completion of the case study it was deemed a successful endeavor. The KROM provided a framework that both production and design staff can use and easily expand. Its use will be to complement current systems in identifying unanticipated consequences of proposed design changes and will enable faster communication routes to key stakeholders whom these design changes will impact.

7. Conclusions

This paper outlines research which provides a rethinking of product part management, taking an assembly based hierarchical view and turning it into a reticulated mesh of cross-dependencies. The Kendrick Reticulated Ontology Model (KROM) will allow a designer to be better poised to predict the impact of a design change on other parts of the system. It will also allow production staff to see how connections between components exist and therefore see the direct impact of the current parts they are working with have on the surrounding parts. This will allow first, second, third etc. order connections in complex products to be easily interrogated.

Secondly, this paper has employed network analysis methods to interrogate design robustness through component connectedness. The ranked component list allows designers to consider the benefit afforded by design changes, outweighed by the impact of component connectedness.

Finally process and product is linked through the methods outlined in this paper. In identifying a current disconnect in design and production communication, the inclusion of tooling on the network has closed the gap in the system. Not only is there a unified model linking component parts to tooling, it was also visible that in including the tooling the connectivity of the graph changes.

It would be possible to continue this beyond assembly and include full manufacturing processes information as forms of connections. This could link to the amount of energy or cost to produce an individual part. The potential to include addition connection themes, such as energy, cost, manufacturing processes, assembly implications and time to deliver metrics will allow this tool to be suited to a range of functions in the engineering domain – meeting a host of needs. In order to remain meaningful and not become lost in noise a layered system can be applied, so that the connections a user is interested in can be toggled on and off.

8. Future Work

In order to further this research consideration must be made regarding graph population. For the purpose of this paper the graph was populated manually, engaging the stakeholders to find the links between components. However an automated approach would be beneficial as it would free the user from manually including connections. This can be achieved using a reasoning engine which infers logic from known facts [15] [16]. Using a reasoning tool, such as Jess [17], known rules can be input for components and inferred rules can be automatically produced.

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