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A network perspective for the analysis of bill of material

Matteo Cinelli[a], Giovanna Ferraro[b], Antonio Iovanella[b,]*,

Giulia Lucci[b], Massimiliano M. Schiraldi[b]

[a]*ISC-CNR Uos "Sapienza", Via dei Taurini, 19 00185, Rome, Italy*
[b]*Department of Enterprise Engineering, University of Rome Tor Vergata, Via del Politecnico, 1 00133, Rome, Italy*

* Corresponding author. Tel.: +39 6 72597788. *E-mail address:* antonio.iovanella@uniroma2.it

Abstract

A Bill of Materials, or Product Structure, is a diagram that lists all the components, intermediate assemblies, sub-components and parts necessary to produce one unit of a finished product, or end part. It is represented as a tree structure with hierarchical relationships among diverse components and materials. The aim of this paper is to propose two procedures to convert single and multiple bills of materials into networks. These procedures exploit the potentialities of networks analysis, offering new viewpoints in terms of representation and extractable informative content, and hence attaining insights into the criticalities of parts and components. Throughout the paper, some network measures are described in terms of practical implications in industrial management, such as product functional design and variety reduction programs.

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Keywords: Variety reduction; Material management; Bill of material; Product structure; Complex networks; Page rank

1. Introduction

Complex networks are important instrument generally used to describe and analyze the structure and dynamical behaviors of many real-world phenomena [1]. The potentialities of such a tool, in terms of representation and analysis, are utilized in different fields in order to identify critical and significant elements and the processes in which they are involved. The use of the centrality measures represents an example of how complex networks are applied, as well as other paradigms at both microscopic and macroscopic levels of detail may be reasonably reported [2].

Lately, researches in the field of operations, risk and supply chain management have exploited complex networks with the purpose of gain novel and important insights into such kinds of topics [3], [7].

A Bill of Materials (BoM) is a diagram that lists all the components and parts required to produce one unit of a finished product or end part. It is often represented as a structure made of hierarchical relationships among different components and materials.

Diverse contributions related to BoM utilization in industrial environment were provided in the past. Indeed, BoM analysis was applied to different business topics such as product data representation in industrial automation, mass customization and variety management, new product development, business management software improvement, forecasting of the product portfolio dynamic behavior and supply chain risk management.

The complex network theory has been already utilized in certain previous contributions, In particular, for analyzing product composition and assembly, studying product structure as a weighted directed graph where parts are denoted as the nodes and relations among them are represented as the links [4]. The majority of these contributions that applied complex network theory to product structure tackled the product design phase, investigating both topological models of parts relation networks and their dynamic behavior. However, these studies are mostly related on confirming the features of scale-free

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networks of component relationships [4], [5] [6] though, it is interesting to consider also the component relationships and their dynamic.

The analysis of BoM data may offer significant information concerning the criticality of materials and semi-finished products, advising how the different components may impact on the production and availability of finished products. Nevertheless, this analysis is difficult to perform due to the huge amount of data that should be treated, particularly when it is carried out at an aggregated level; for example, for parallel processing all the BoMs of a product portfolio. Hence, the complex networks, which can be applied in relation to centrality measures and graphical representation, are useful for the detection of some critical aspects related to materials and intermediate product management.

In production planning, a BoM is linked to production orders, since it defines the relationship between components, and semi-finished or raw materials, either in stock or to be purchased. The stratification of all production orders requires a consumption pattern of these parts. Inventory policies and management decisions about target inventory levels should deem these patterns, and the parts criticality in the whole manufacturing process. In sight of this, it results more critical a component shared by all the BoMs of a product portfolio than a component used in only one finished product.

Thus, starting from the contribution [7], this paper examines additional aspects of the BoM represented as a network, as well as the potential practical implications in terms of inventory and production planning.

The paper is structured as follows: Section 2 establishes a common vocabulary in order to invoke concepts belonging to the graph theory, applicable and functional to BoMs analysis. Section 3 shows two pre-processing steps that should be used when operating on the BoM data in order to make them usable for an appropriate network analysis. Section 4 provides interpretation of the centrality measures in manufacturing context. Section 5 offers the conclusions.

2. BoM as a graph

A BoM is a list of immediate components of a specific product, and it reports the relationships among them. Among the various representations [8] [9], this paper considers the standard as provided by the ISO 10303-44:2014 (*Industrial automation systems and integration -- Product data representation and exchange -- Part 44: Integrated generic resource: Product structure configuration*) that is the classical tree shaped representation where, in the hierarchy of the BoM, the finished product is placed at the highest level, and is made of parts such as raw materials, semi-finished products or components, (herein respectively referred to as starting materials, sub-assemblies or assemblies). These relationships therefore describe a predecessor-successor structure. As a BoM shows all of the parts found in parent-children relationship, this relation is represented as a directed link from parent node to child node, resulting in a directed and acyclic connected graph. Similar structures have been widely analyzed and used in graph theory and are called as directed trees. Furthermore, as the BoMs usually comprises the quantities of each part number required to build an assembly, this could be considered as the weight of a link. The resulting structure is a weighted directed tree, where:

- Each part having $d_{in} = 0$ is a finished product.
- Each part having $d_{in} \neq 0$ and $d_{out} = 0$ is a starting material (or a part that enters the production process as it is, i.e. a purchased item).
- Each part having $d_{in} \neq 0$ and $d_{out} = 0$ is an assembly or sub-assembly.
- Each part having $d_{in} \neq 0$ and $d_{out} = 0$ and at least a neighbor with $d_{out} = 0$ is directly composed of starting materials.

These statements allow us to detect the role of nodes and their level in the corresponding BoM.

For review of the employed notation, please refer to the Nomenclature box.

Nomenclature

G	a graph of n nodes and m links
d_i	degree of node i, i.e. number of incident links upon it
d_i^{in}	in-degree, number of edges with head i
d_i^{out}	out-degree, number of edges with tail i
s_i	strength of node i, which is the total weight of the edges incident upon it
s_i^{in}	in-strength of node i, which is the total weight of the in-edges incident upon it
s_i^{out}	out-strength of node i, which is the total weight of the out-edges incident upon it
c_B	*betweenness centrality*, determines the number of times a node acts as a bridge along the shortest path between two other nodes
p_k	*PageRank* centrality, indicates that a node is important if it is linked to other important nodes

3. BoM pre-processing steps

The main difference between the classical tree-like structure used to represent a BoM and the graph theoretical tree structure concerns the node repetition, which is permitted in the former but not in the latter. For this reason, BoMs need the contraction of replicated nodes in order to be treated with a solid and robust theoretical framework.

During the transfer of the BoM towards the tree-like structure and during the contraction of replicated nodes, the attributes of the items may be kept, summing up the quantities involved in the realization of higher-level items. When we consider, as nodal attribute the quantities of each item involved in the realization of one unit of an end product, these values are represented as edge weights in the contracted network. Indeed, the quantity is an attribute that characterizes both the node itself and the relationship with its predecessor, which requests that specific quantity in order to be realized. The choice to assign the quantity over the links of the networks is reasonable, since the contraction procedure, when needed, reduces the number of nodes, while the number of relationships among nodes remains the same. In the case of node labels or other categorical attributes, these can be kept as

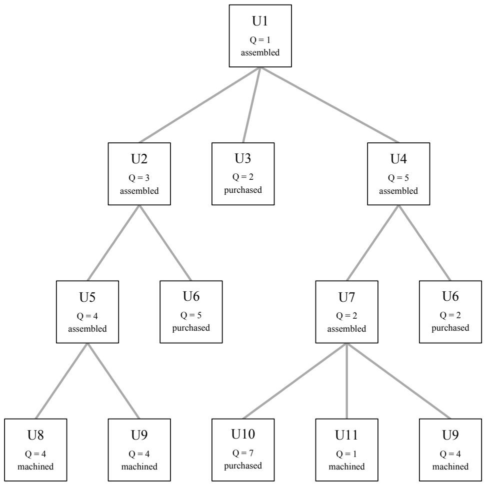

Fig. 1. An example of BoM before the contraction procedure.

a set of nodes characteristics in order to avoid a loss of information.

We apply a procedure that we define as *contraction of bill of materials*. This method requires a manipulation of the product structure such that each node appears only once. Thus, we repeat to the aforementioned node contraction to implement this process.

In so doing, we assume that links are directed from higher-level nodes to lower level-nodes in order to represent dependencies and that a node can have other ones, at different levels, pointing to it.

We consider the set of products that share some components in their BoM as $P = \{P_1, P_2, ..., P_i, ..., P_n\}$ and we named the components as U_i.

As an example, Fig.1 depicts a BoM of a certain product P_i. Fig. 2 shows the result of the contraction procedure that unifies the two nodes U_6 and U_9, allowing the possibility of other nodes to point to them. In the reported case, nodes U_2 and U_4 point to U_6 while nodes U_5 and U_7 point to U_9. The contraction procedure drops the graph theoretical tree structure, generating a slightly diverse structure, that is still formally correct, in which nodes are allowed to have $d_{in} \geq 1$.

Furthermore, Fig. 2 describes the contracted BoM where the links are scaled by their weights and the nodes are scaled by their in-strength.

When we have to deal with many BoMs of different products that share some components, a one by one evaluation may become very difficult and sometimes unfeasible. Indeed, when the number of items increases, so does the complexity of the number of considered products. For this reason, the evaluation of critical nodes requires the introduction of an *aggregation procedure*.

We use the aggregation procedure that is a common way to investigate systems that interact on multiple layers and which sums up the data from different layers into a single one [10]. From this procedure results a weighted network in which the link weights between two nodes derive from a linear combination of the weights between those same nodes from each of the layers.

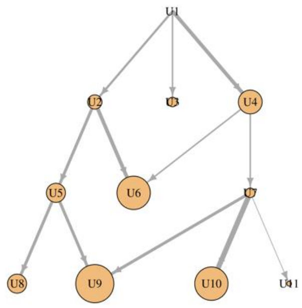

Fig. 2. Contracted BoM for Product 1 in which node size is proportional to the in-strength.

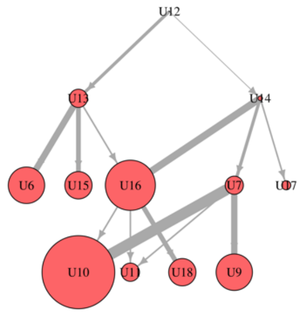

Fig. 3. Contracted BoM for Product 2 in which node size is proportional to the in-strength.

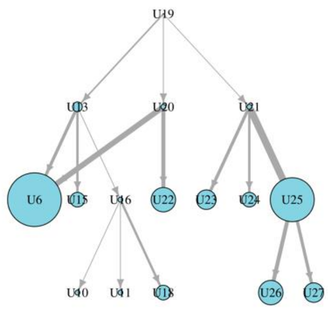

Fig. 4. Contracted BoM for Product 3 in which node size is proportional to the in-strength.

With reference to the weighted version of the three example BoMs (Fig. 2-4), it is possible to aggregate them considering a single copy of each end product or a certain mix of end products. Thus, we suppose to have a production plan in the next period of time that requires 2 units of P_1, 3 units of P_2 and 10 units of P_3. Fig. 5 and 6 show two different aggregation procedures in which the size of the links is proportional to their weight whilst the size of the nodes is proportional to their total strength, i.e. to the global involvement of nodes within the network.

It is important to point out that the proposed procedures can be applied to any kind of BoM and therefore are valid for any number of products and production plans.

Fig. 7 represents the role of betweenness centrality by plotting the size of the nodes proportionally to their betweenness centrality values in case of production plan based network. Similarly, Fig. 8 shows the role of the PageRank centrality.

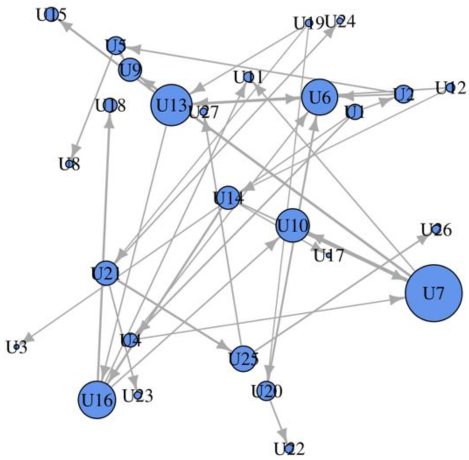

Fig. 5. Aggregation of the three BoMs of Fig. 2-4 considering one unit per each end product.

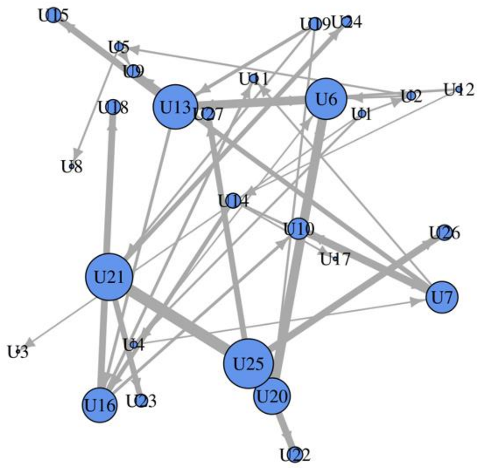

Fig. 6. Aggregation of the three BoMs of Fig. 2-4 considering a number of units that is based on the described production plan.

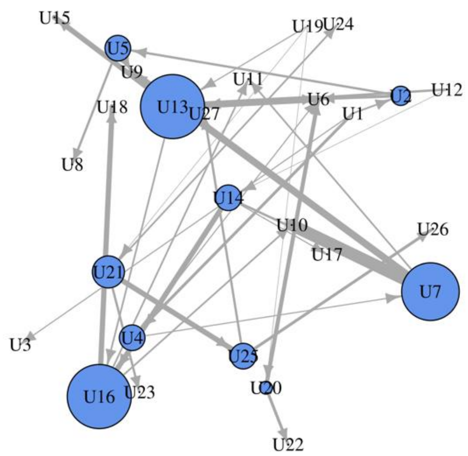

Fig. 7. Representation of an aggregated BoM in which the node size is proportional to its betweenness centrality.

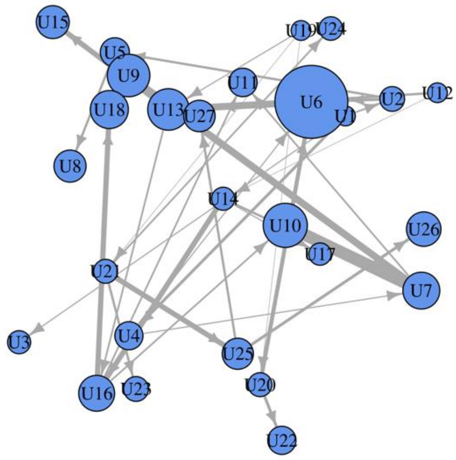

Fig. 8. Representation of an aggregated BoM in which the node size is proportional to its PageRank centrality.

4. Interpretations of centrality measures

The steps previously described are functional to the BoM processing. The results deriving from the analysis of centrality measures can be interpreted in relation to the BoM of a single product as well as to the aggregated BoMs of all the products belonging to the portfolio, or to its subsets.

In particular:

- In-degree, that is the number of head ends adjacent to a component, represents the number of finished products (or, respectively, sub-assemblies and assemblies) composing of a specific assembly (or, respectively, sub-assemblies and starting materials).
- Out-degree, that is the number of tail ends adjacent to a component, represents the number of assemblies (or, respectively, sub-assemblies and starting materials) from which the finished product (or, respectively, the sub-assembly and the assembly) is composed.
- In-strength, that is the sum of the weight of head ends adjacent to a component, represents the overall participation of a part in the product considering the occurrence in the BoM network in which it is involved as well as the required quantities.
- Betweenness, that is the extent to which a component lies on the paths between other components, represents a way to measure how much it is critical to manage an assembly based on the dependencies of sub-assemblies and starting materials.
- PageRank, a node has high rank if the sum of the ranks of its in-edges is high. This covers both the case when a node has many in-edges and when a page has a few highly ranked in-edges [1] [11]; PageRank quantifies the overall importance of a component based on the relative importance of the components it is part of. It originates from Google co-founder Larry Page and it is used to rank website in Google's search results [11].

Regarding the properties of the single BoM, the analysis of the case of a single final product focuses on product (or eventually family) criticalities. Indeed, the higher the number of components or parts composing the final product, the more challenging the required efforts are in terms of material management and inventory, as well as production planning, where intermediate processing phases are present. In particular, the numerousness of different starting materials related to a final product is a measure of the criticality of the supply processes for that product. On the other hand, a measure of the criticality of the production planning process is the numerousness of different assemblies and sub-assemblies related to a final product.

In order to carry out an in-depth analysis of the dependency of a final product on a specific starting material, or sub-assemblies or assemblies, the strength should be applied since can be interpreted as the overall participation of a part in the final product, considering at the same time the occurrence in the BoM network in which it is involved and the required quantities. Consequently, the evaluation of the strength measure highlights the level of dependence of a final product on the starting materials, assemblies or sub-assemblies. This information, together with the information regarding quantities, as reflected in the thickness of the edges in the figures, could help in analyzing the risk specificity.

For example, considering Product 2 in Fig. 3 the item U_6 has a relatively high in-strength $s_{in} = 8$ (as shown by the size of the node) but low in-degree $d^{in} = 1$ while the item U_{11} has a relatively higher in-degree $d^{in} = 2$ but lower in-strength $s^{in} = 4$ signifying that the former is required in a higher quantity by only one element while the latter in required less in quantity but more in numerosity. However, Fig. 3 shows that the most critical item of Product 2 is U_{10} that has both a relatively high in-degree $d^{in} = 2$ and in-strength $s^{in} =10$. Thus, if the part number has a high in-degree and a high in-strength (i.e. a large number of semi-finished and finished products pointing to it), we can assume that the risk of production re-scheduling of such semi-finished or finished products will be higher. Conversely, if the part number has a high in-strength but a lower in-degree (i.e. the number of finished and semi-finished products is low, while the quantities used are high) the risk of re-planning will be limited.

In the case of aggregate BoM, it becomes important the overall part number centrality when studying its properties; in particular, to the starting materials, sub-assemblies and assemblies. The analysis of parameters, such as strength and in-degree, indicates the centrality of the part in the manufacturing process of the final products. The strength could be taken into consideration when we investigate the impact on production planning and it should be considered how to manage the related supply or production. Indeed, more the part is shared among BoMs, more the reordering and production-planning criteria should be accurately managed. The in-degree value points out the number of finished products that uses the part, i.e. the starting material, sub-assembly, assembly.

By comparing the two Fig. 5 and 6, we notice how the presence of a production plan alters the criticality associated to each component. For instance, when we do not consider the production plan, the node U_7 is the most critical (see Fig. 5), showing an overall strength of $s_7 = 42$ but, when we consider the aggregated BoM (see Fig. 6), such item is not that critical anymore and in this case the item U_{25} became now the most critical with a value of $s_{25} = 180$.

Metrics such as in-degree and strength could be used by materials managers and inventory controllers as inputs for inventory control analysis. Although different criteria are listed in literature to classify parts in material management, in-degree and strength could represent an additional parameter to find the most critical parts or supplies.

The application of the same metrics to product family aggregated BoMs permits to evaluate the similarity of part sets. Since similarity ratios could assist in the application of methods for the standardization and rationalization of components and product structures, the in-degree and strength analysis can support the functional design in order to comply with diversification as well as cost control needs. To lower the operating costs induced by the actual industrial trend towards products diversification, techniques such as Variety Reduction Program (VRP) can be considered, pushing the product designers to address diversification while eliminating potentially redundant product variants.

By calculating of the number of parts and modules (structural components), VRP techniques incorporate such ratio as the Part Index, which are useful in empirically measuring the incidence of the introduction of a new part into the aggregated product structure.

In-degree and strength allow us to consider accurately this phenomenon, calculating more accurate indexes, and reducing the efforts involved in applying variety control techniques. The effect of the application of these principles is not restricted to the simplification of the structure of the products from a design point of view. A more rational structure of the product range entails a reduction in the workload for purchasing and manufacturing processes. Thus the proposed methodology offers way to different techniques aiming to reduce the overall operating costs through a rationalization of the product structure.

5. Conclusions

In this paper, we considered the interrelation between product structure in manufacturing systems and complex networks, assessing the practical implications of the analysis of the BoMs network through some centrality measures. We introduced two formal procedures to pre-process BoM data and set the network structures necessary in order to perform centrality measure analysis. We revealed the possibility of using such metrics to gain insights into the operations management field. In particular, we highlighted that some practical implications can be derived from the analysis of both the single BoM and the aggregated BoM. The latter is the main contribution in terms of data manipulation, since it consents to extract information in a way that was previously difficult to obtain.

The graphical structure of the obtained complex networks combined with the data visualization tools allowed us to identify at first glance the critical elements in the network, considering different perspectives that could be used in a wide range of operations management applications.

Future development may examine the in-depth analysis of the highlighted implications, possibly by means of a richer quantity of data. Moreover, a wide investigation into the interpretation of a larger set of centrality measures able to provide different meaning of criticality could be of great interest.

The introduced procedures can be also exploited in order to obtain more insights in order to support operations management optimization techniques in manufacturing processes, such as modular product design, variety reduction programs, inventory and production planning optimization.

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