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A network perspective on the visualization and analysis of bill of materials

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Abstract

A bill of materials (BoM), or product structure, 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 tree structure with hierarchical relationships among different components and materials. In this article, we introduce two procedures to convert single and multiple BoM into networks. These procedures allow us to leverage the potentialities of networks analysis, providing new perspectives in terms of representation and extractable informative content, and thus gaining insights into the criticalities of parts and components. We conclude interpreting some network measures and their outcomes in terms of practical implications in industrial management, for example, product functional design and, above all, variety reduction programs.

Keywords

Variety reduction, material management, bill of materials, product structure, complex networks

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Introduction

The increasing interest in holistic approaches devoted to the study of reality and their success in detecting emerging and critical phenomena has been captured by many researchers, who exploited such approaches in order to solve a number of practical problems. The usage of neural networks, machine learning, evolutionary computation, fractals, and, more generally, the theory of complexity is now established within science and well introduced within practice.[1,2]

Within this framework, complex networks represent a solid and reliable tool, widely used for the investigation of many real-world phenomena.[3] The potentialities of such an instrument, in terms of representation and analysis, are now used in many domains of science in order to detect critical and important elements and the processes in which they are involved. A first example of how complex networks are applied may be represented by the use of centrality measures, though many other examples at both microscopic and macroscopic levels of detail may be reasonably reported.[4] Additionally, in recent times, studies in the field of operations, risk and supply chain management have exploited complex networks in order to gain novel and important insights into such kinds of topics.[5,6]

For example, in the field of operations management, complex network analysis is mainly associated with issues relating to the supply chain.

Indeed, when analyzing supply chain structure as a complex network with respect to material and information exchange, nodes represent organizations and edges represent connections among them. Since it has been demonstrated that the supply chain structure affects company performance in terms of operational efficiencies, centrality measures have been applied to evaluate supply chain

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performances and their corresponding risk profile.[6–9] Complex networks have also been used in industrial big data applications: indeed, organizations are continuously generating huge data sets within information systems. These include historic demand and forecasting data, replenishment lead times, recorded service level, and replenishment orders costs.[10] Some of these, such as the ones related to supply and demand fluctuations, impact on inventory levels and could help in managing and optimizing inventory issues. It has also been demonstrated how they can help in handling the most complex retail, wholesale, and multichannel challenges in inventory management,[11] as well as predict inventory needs in case of fluctuating customer demands through statistical forecasting techniques[12] and in reducing inventory costs.[13] Data could be used to define stocks in multiechelon distribution networks[14–16] and define the right inventory level in terms of demand variability at the network nodes,[17,18] which also helps in defining the appropriate safety stock level.[19,20]

In addition to supply chains, other industrial data structures could be represented as networks and analyzed through the related measures. 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, and it is often presented as a structure made of hierarchical relationships among different components and materials.

Several contributions linked to BoM utilization in the industrial context were provided in the past. BoM analysis was applied to a wide range of business issues such as mass customization and variety management, product data representation in industrial automation, business management software improvement, new product development, supply chain risk management, and forecasting of the product portfolio dynamic behavior. In order to summarize related contributions, Table 1 considers main research perspectives about BoM literature.

Table 1. Main research perspective about BoM literature.

Covered aspects/addressed issues	Authors
Mass customization and variety management	Jiao et al.[21]
Product data representation in automation	British Standard,[22] Raharno and Martawirya[23]
Interaction with business management software	De Heij and Caubo,[24] Lee et al.,[25] Wu et al.,[26] Zong et al.[27]
New product development	Bandinelli et al.,[28] He et al.,[29] Regattieri et al.[30]
Supply chain risk management	Takata and Yamanaka[31]
Topological models and dynamic behavior	Liu and Qi,[32] Xi and Zheng[33]

BoM: bill of materials.

Some of the previous contributions already applied complex network theory in their works: they analyze product composition and assembly, considering product structure as a weighted directed graph where parts are represented as the vertexes and relations among them are represented as the edges.[34] Most of those studies that applied complex network theory to product structure addressed the product design phase, analyzing both topological models of parts relation networks and their dynamic behavior. Nevertheless, these works are mainly focused on verifying the characteristics of scale-free networks of component relationships[32–35]; in spite of this, it is actually interesting to focus also on component relationships and their evolution.

Indeed, drilling down BoM data may provide relevant information regarding the criticality of materials and semifinished products, suggesting how these may impact on the production and availability of finished products. However, this kind of analysis is difficult due to the huge amount of data that needs to be treated, especially when the analysis is performed at an aggregated level; for example, for concurrently processing all the BoMs of a product portfolio. Thus, the use of complex networks, both in relation to centrality measures and graphical representation, is useful for the evaluation of some critical aspects related to materials and intermediate product management.

In production planning, a BoM is tied to production orders, describing the relationship between components, and semi-finished or raw materials, either in stock or to be purchased (parts). The stratification of all production orders entails a consumption pattern of these parts. Inventory policies and strategical decisions about target inventory levels should not only consider these patterns but also the parts criticality in the entire manufacturing process. For example, a part shared by all the BoMs of a product portfolio is definitely more critical than a part found in only one finished product. Therefore, this article consists of an exploratory study that examines the potential insights of analyzing the BoMs networks, as well as the potential practical implications in terms of inventory and production planning, laying the basis for further in-depth optimization techniques.

The article is structured as follows: "Theoretical background" section explains the theoretical background and establishes a common vocabulary in order to invoke concepts belonging to the graph theory, applicable and functional to BoMs analysis. " BoM preprocessing steps" section shows two preprocessing steps that should be used when operating on the BoM data in order to make them usable for an appropriate network analysis. These consist of the contraction of the BoM, that is the action of collapsing all nodes with the same label in such a way that this latter appears only once in the network, and in the aggregation of all product BoMs in an aggregated BoM, by summing up all the connections among the nodes of each BoM in a single network. "Complex networks insights and their implications" section explains complex network insights and the related implications considering potential outcomes of the analysis of the Single BoM, that is, the single product structure, and the aggregated BoM, that is, the collapsed network of all the managed product structures. The final section presents the conclusions.

Theoretical background

Applicable graph theory

Graphs are mathematical structures used to model either symmetric or asymmetric relations that occur in systems. In the former case, we represent relations using undirected graphs, while in the latter case, we necessitate a more general model represented by directed graphs.

A directed graph or digraph G is a triple consisting of a vertex set $V(G)$, an edge set $E(G)$, and a function assigning each edge an ordered pair of vertices.[36] The first vertex of the ordered pair is the tail of the edge and the second is the head; together they are endpoints. We say that an edge is an edge from its tail to its head. In a digraph, a loop is an edge whose endpoints are equal, while multiple edges are edges having the same ordered pair of endpoints. A digraph is simple if each ordered pair is the head and tail of at most one edge; one loop may be present at each vertex. However, in many cases, loops are not allowed in simple digraphs and we consider simple digraphs to be without loops. In a simple digraph, we write e_{ij} for an edge with tail i and head j. If there is an edge from i to j, then j is a successor of i, and i is a predecessor of j.

The underlying graph of a digraph is the graph obtained by treating the edges of G as unordered pairs. A digraph is weakly connected if its underlying graph is connected, while a digraph is strongly connected if for each ordered pair (i,j), there is a path from i to j. The degree of a vertex i in a graph G, written d_i, is the number of edges incident to i. Let i be a vertex in a digraph. The out-degree d_i^{out} is the number of edges with tail i. The in-degree d_i^{in} is the number of edges with head i. The out-neighborhood or successor set N_i^{out} is $\{j \in V(G) : i \rightarrow j\}$. The in-neighborhood or predecessor set N_i^{in} is $\{j \in V(G) : j \rightarrow i\}$.

A tree is a connected acyclic graph; a leaf is a vertex of degree 1.

In a graph G, a contraction of edge e with endpoints i,j is the replacement of i and j with a single vertex whose incident edges are the edges other than e that were incident to i or j.

A vertex contraction, or node contraction, is the replacement of two (or more) nodes with a single node i such that i is adjacent to the union of the nodes to which the other nodes were originally adjacent. A vertex contraction, or node contraction, of a pair of vertexes i and j of a graph produces a graph in which the two nodes i and j are replaced with a single node k such that k is adjacent to the union of the nodes to which i and j were originally adjacent. In vertex contraction, it doesn't matter if i and j are connected by an edge; if they are, the edge is removed upon contraction. A contraction can be performed on more than two nodes at the same time.

Another representation of graphs that helps in going beyond their topological inspection is represented by weighted graphs. Weighted graphs constitute a generalization of unweighted graphs since they include links whose weights represent the intensity of interaction between couples of nodes. An extension of the degree is represented by the strength s_i, which is the total weight of the edges incident to i. The concept of strength, in case of directed graphs, extends to in-strength and out-strength. The strength integrates information about the node connectivity and the weight of its links. However, s_i is not an exhaustive measure as it only considers the level of involvement of a node in the system and not explicitly the number of other nodes to which it is linked. Thus, it is important to include in the network analysis both degree and strength in order to indicate the overall involvement of a node in the neighboring network.[37–39]

The *betweenness centrality* determines the number of times a node acts as a bridge along the shortest path between two other nodes. In formula: $c_B(i) = \sum_{k \neq i \neq j} \sigma_{kj}(i)/\sigma_{kj}$, where $\sigma_{kj}(i)$ is the number of shortest paths from k to j containing node i and σ_{kj} is the number of shortest paths from k to j.

The words vertex, node and edge, link will be used interchangeably throughout the article.

Interpretation of the BoM in terms of graph theory

All the represented measures can find a specific meaning within the analysis of product structure, if the appropriate analogies between the bill of materials and the networks are defined.

Given a specific product, a BoM is a list of its immediate components by which it is built and their relationships. Among the different representations,[21] in this article we consider 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 positioned 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, subassemblies, or assemblies). These relationships consequently define a predecessor–successor structure. As a BoM displays all of the parts found in parent–children relationship, this tie could be represented as a directed edge from parent node to child node, resulting in a directed and acyclic connected graph. Similar structures have been extensively studied and used in graph theory and are known as directed trees. In addition, as the bill of materials typically includes the quantities of each part number required to build an assembly, this could be interpreted as the weight of an edge. 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 $d_{out} \neq 0$ is an assembly or subassembly.
- Each part having $d_{in} \neq 0$, $d_{out} \neq 0$ and at least a neighbor with $d_{out} = 0$ is directly composed of starting materials.

Using these statements, we are able to identify the role of nodes and their level in the corresponding BoM.

BoM preprocessing steps

Contraction of bill of materials

The main difference between the BoM represented as a tree-like structure 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 duplicated vertices in order to be treated with a solid and robust theoretical framework.

During the transfer of the BoM towards the tree structure and during the contraction of multiple nodes, the attributes of the items may be kept, summing up the quantities involved in the realization of higher level items. When we consider a special nodal attribute, that is, the quantities of each item involved in the realization of one unit of an end product, these values become edge weights in the contracted network. Indeed, the quantity is an attribute that characterizes the node itself as well as the relationship with its predecessor, which necessitates that specific quantity in order to be realized. The decision to assign the quantity over the edges 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 a set of nodes characteristics in order to avoid a loss of information.

The following procedure, which we define as *contraction of bill of materials*, consists of a manipulation of the product structure such that each node appears only once. To implement this procedure, we recur to the aforementioned node contraction. In our representation, 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. Other approaches regarding the use of BoMs in terms of complex networks[34,35] have not used this procedure to manipulate BoMs, and have avoided to incorporate any formal and explicit method, which we consider to be fundamental in comprehending the construction of the whole framework and the usage of complex networks to represent product structures.

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

Let us consider a certain product P_i that shows a BoM as in Figure 1; in Figure 2, we observe the process of contraction that unifies the two copies of nodes $U6$ and $U9$, which allows the possibility of other nodes to point to them. In this case, nodes $U2$ and $U4$ point to $U6$, while nodes $U5$ and $U7$ point to $U9$. The procedure of contraction, in this case, drops the graph's theoretical tree structure, generating a slightly different structure, that is still formally correct, in which nodes are allowed to have $d_{in} \geq 1$.

Lastly, in Figure 3, we report the contracted BoM where the edges are scaled by their weights and the nodes are scaled by their in-strength.

At the very end of the process, we obtain a weighted graph with directed links from end product to raw materials and whose nodes have attributes that may be either discrete or scalar, that is, any type of metadata. For the adjacency matrices of the contracted BoMs please refer to the supplementary material.

Aggregation of multiple BoMs

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 necessitates the introduction of an aggregation procedure. The aggregation procedure is a common way to examine systems that interact on multiple layers and which sums up the data from different layers into a single one.[40] The resulting network is weighted and the edge weights between two nodes derive from a linear combination of the weights between those same nodes from each of the layers.

In this article, we derive this idea from the multilayer networks literature, considering each (contracted) BoM as a graph in a layer that represents the final product. However, our procedure lacks in some way of the formalism needed by multilayer networks due to the difficulties in clearly defining the role of interlayer links, together with their weights, and other issues concerned with interpreting of specific multilayer measures that conversely are widely used in the investigation of other technological and social networks.[40–42] More specifically, when considering all the items that compose the entire BoMs, we suppose that each node (item) is present in each layer and that all the items that have degrees different from zero are involved in the BoM of that product. For this reason, we may deduce that we are to be closer to a specific kind of multilayer network represented by edge colored multigraphs.

In our case, the aggregation procedure can be performed in two ways: by considering a single copy of each product

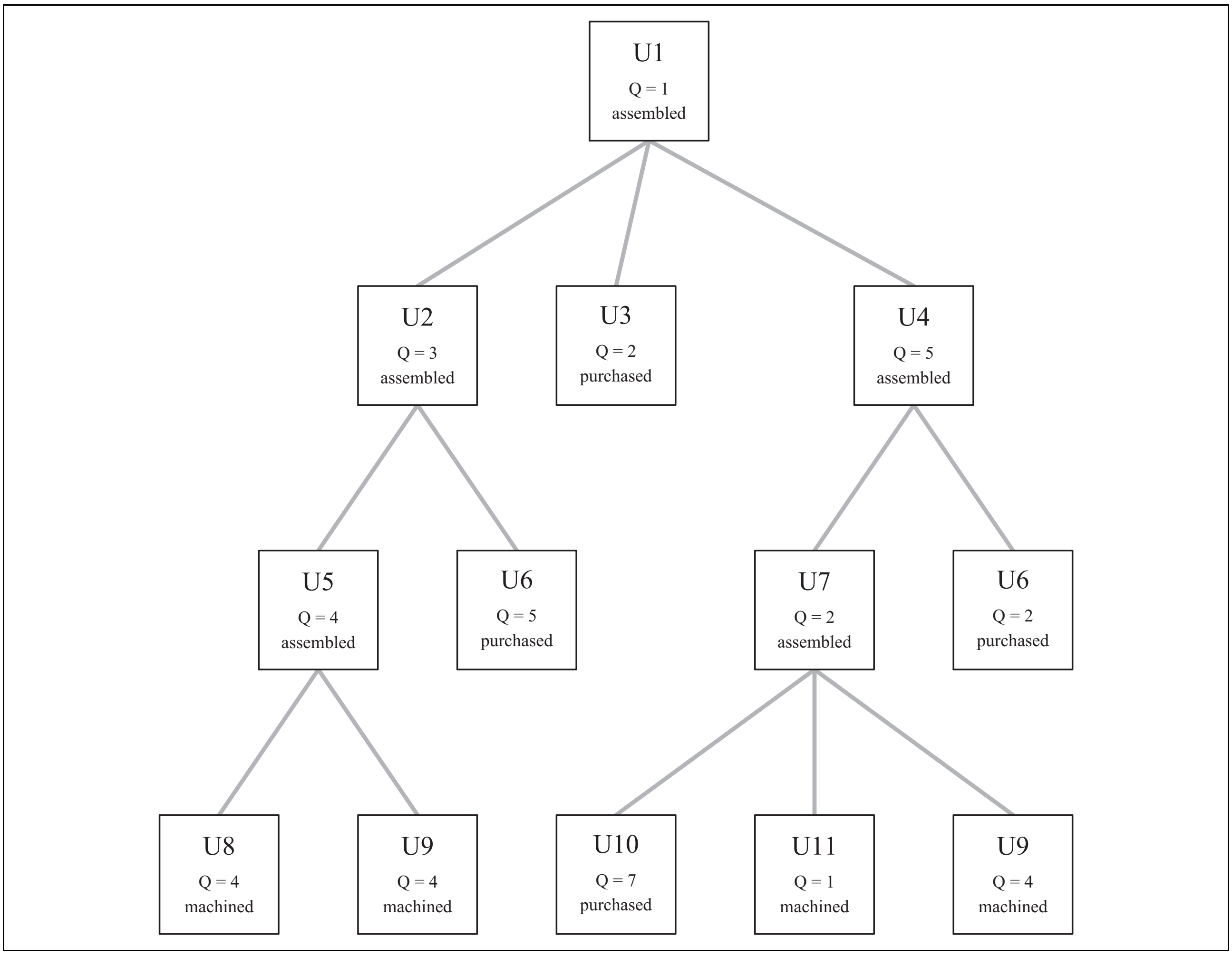

Figure 1. A BoM before the contraction procedure. BoM: bill of materials.

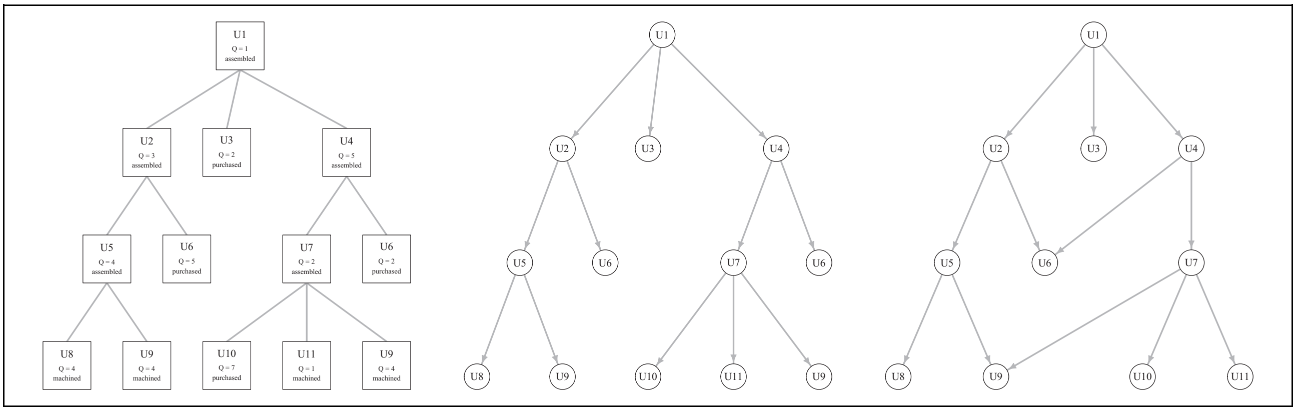

Figure 2. From initial BoM to a directed BoM, and from a directed BoM to a contracted BoM. BoM: bill of materials.

or by considering a number of copies of each product which correspond to the quantity of the product that we actually require over a certain period of time.

The usage of one procedure instead of another might substantially alter the importance that we attribute to specific nodes.

Using the same notation as before, let us firstly consider the binary version (i.e. unweighted) of the contracted BoMs related to three different products as shown in Figure 4.

The BoMs of the three different products can be even represented as a multilayer-like structure observing all the

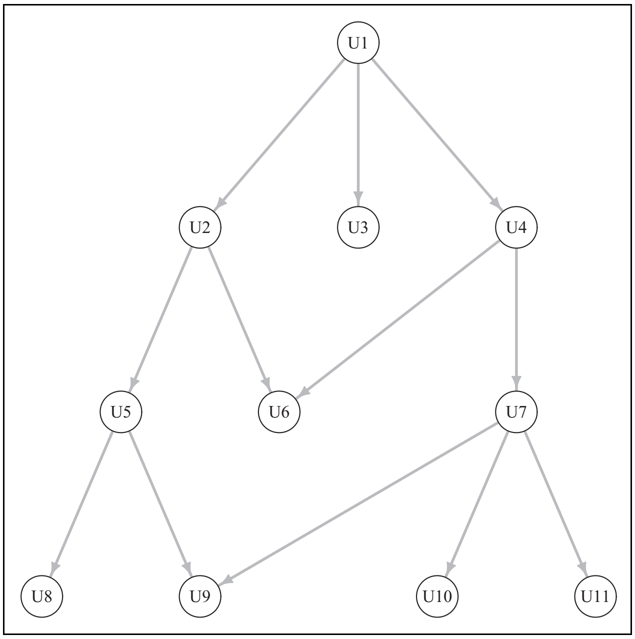

Figure 3. A weighted contracted BoM. BoM: bill of materials.

products simultaneously but represented in their own layer. The representation of BoMs as different connected components in different layers is helpful in order to comprehend and interpret the aggregation procedure. In our representation, shown in Figure 5, the end product, that constitutes the root node of the contracted BoM, gives name to the specific layer into which we observe dependencies.

Therefore, using the aggregation procedure in case of binary networks, we combine the three layers obtaining an aggregated network (Figure 6) that is unweighted and useful in case of topological analysis.

Let us now consider the weighted version of the three BoMs of Figure 7. We can now aggregate them considering a single copy of each end product or considering a certain mix of end products. In particular, 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. The two different aggregation procedures are shown in Figure 8. In the two representations, the size of the edges is proportional to their weight, while the size of the nodes is proportional to their total strength, that is, to the global involvement of nodes within the network.

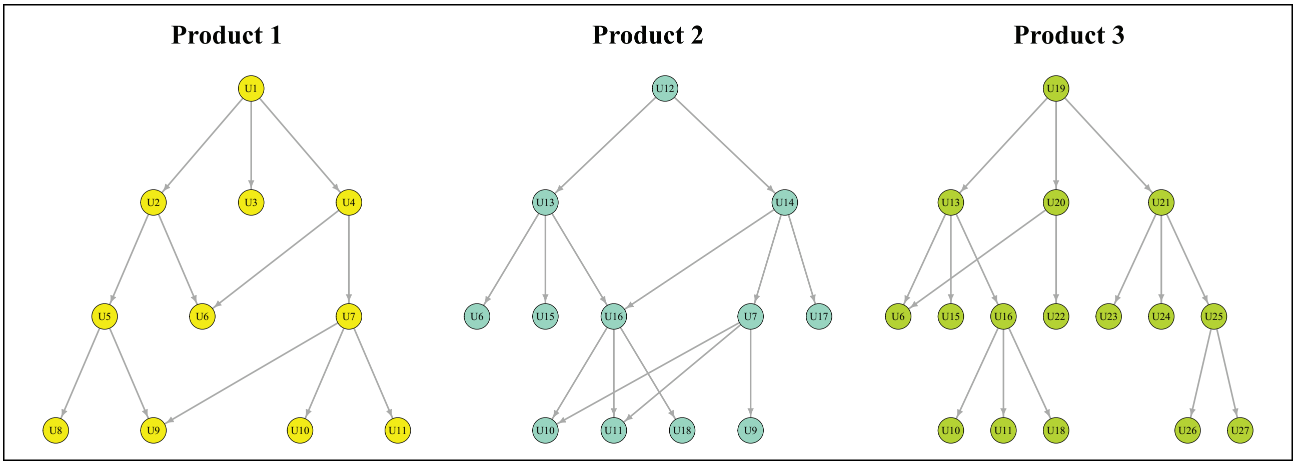

Figure 4. Contracted BoMs of three different products. BoM: bill of materials.

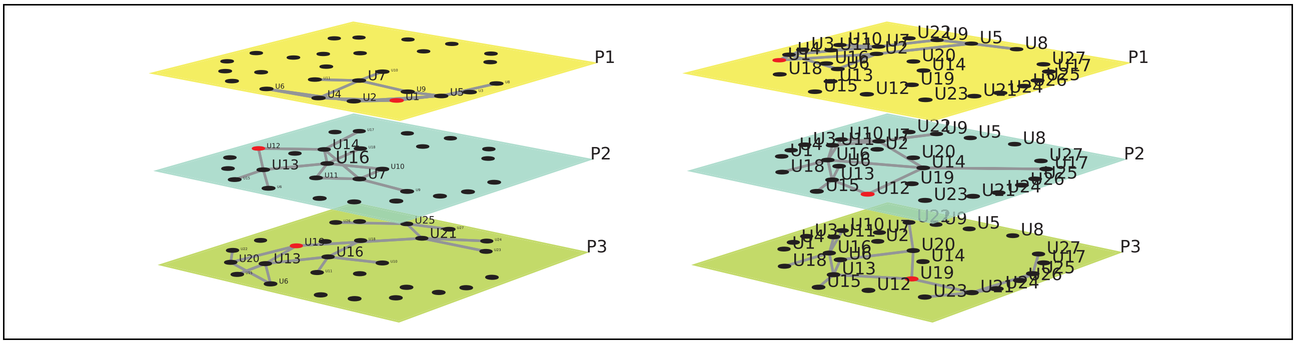

Figure 5. Contracted BoMs represented in a multilayer structure. In the left side, the labels of the nodes have size proportional to their degree. Red nodes represent end products. BoM: bill of materials.

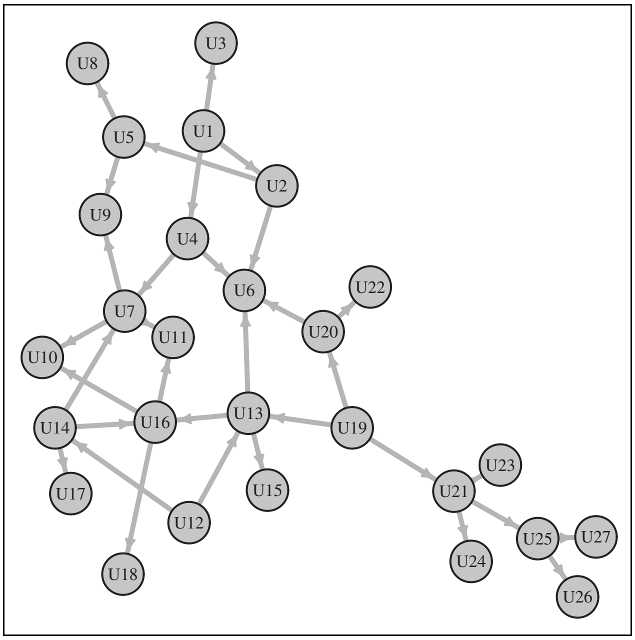

Figure 6. Topological aggregated network of BoMs in Figure 4. BoM: bill of materials.

Note that our procedure is valid for any kind of BoM and therefore is applicable to any number of products and production plans.

Lastly, we show (Figure 9) 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.

Complex networks insights and their implications

General properties and related implications

The steps described in the previous paragraphs are functional to the BoM processing. The results deriving from the analysis of centrality measures can be interpreted in relation to both the BoM of a single product and the aggregated BoMs of all the products belonging to the portfolio, or to its subsets. For this reason, after introducing the general interpretation of the main centrality measures described in the theoretical background, the same are analyzed through consideration of the practical implications in terms of management, both in the case of the single BoM and the aggregated BoM. It is possible to propose a general interpretation of the main values as follows:

- In-degree, that is the number of head ends adjacent to a node, represents the number of finished products (or, respectively, assemblies and subassemblies) composing of a specific assembly (or, respectively, subassemblies and starting materials).
- Out-degree, that is the number of tail ends adjacent to a node, represents the number of assemblies (or, respectively, subassemblies and starting materials) from which the finished product (or, respectively, the assembly and the subassembly) is composed.
- In-strength, that is the sum of the weight of head ends adjacent to a node, represents the overall participation of a part in the product considering both the occurrence in the BoM network in which it is involved and the required quantities.
- Betweenness, that is the extent to which a node lies on the paths between other nodes, represents a way to measure how much it is critical to manage an assembly based on the dependencies of subassemblies and starting materials.

Properties of a single BoM and their implications

In this section, centrality measures are analyzed and interpreted in relation to a single BoM. Evaluating what the centrality measures mean is approached from the point of view of the single final product and its components. The analysis of the single final product focuses on product (or eventually family) criticalities. Indeed, the higher the number of components or parts of which the final product is composed, the more challenging the required efforts are in terms of inventory and material management, 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, the numerousness of different assemblies and subassemblies related to a final product is a measure of the criticality of the production planning process.

In order to carry out an in-depth analysis of the dependency of a final product on a specific starting materials, or assemblies or subassemblies, the strength measure should be applied. Indeed, the strength should be interpreted as the overall participation of a part in the final product, considering both the occurrence in the BoM network in which it is involved and the required quantities. Therefore, the evaluation of the strength measure highlights the level of dependence of a final product on the starting materials, assemblies or subassemblies. This information, coupled with the information regarding quantities, as reflected in the thickness of the edges, could help in analyzing the risk specificity. For example, considering product 2 in Figure 7, the item U6 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 U11 has a higher in-degree $d_{in} = 2$ but lower in-strength $s_{in} = 4$, indicating that the former is required in a higher quantity by only one element, while the latter is required less in quantity but more in numerosity. However, as Figure 7 shows, the most critical item of product 2 is U10 that has both a high in-degree $d_{in} = 2$ and in-strength $s_{in} = 10$. Thus, if the part number has a high in-strength and a high in-degree (i.e. a large number of finished and

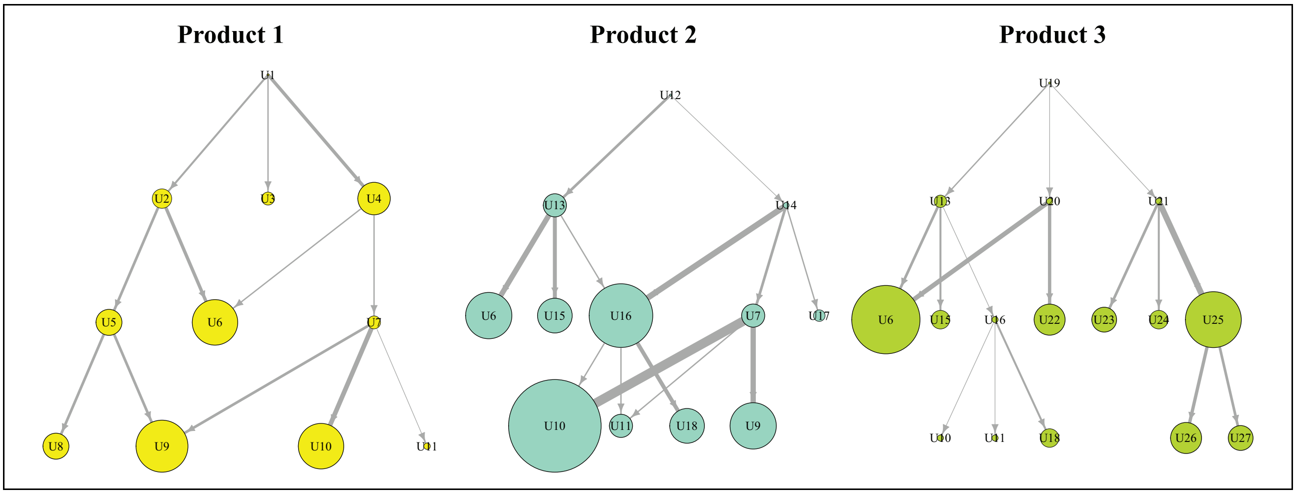

Figure 7. Contracted BoMs of three products in which nodes size is proportional to the in-strength. BoM: bill of materials.

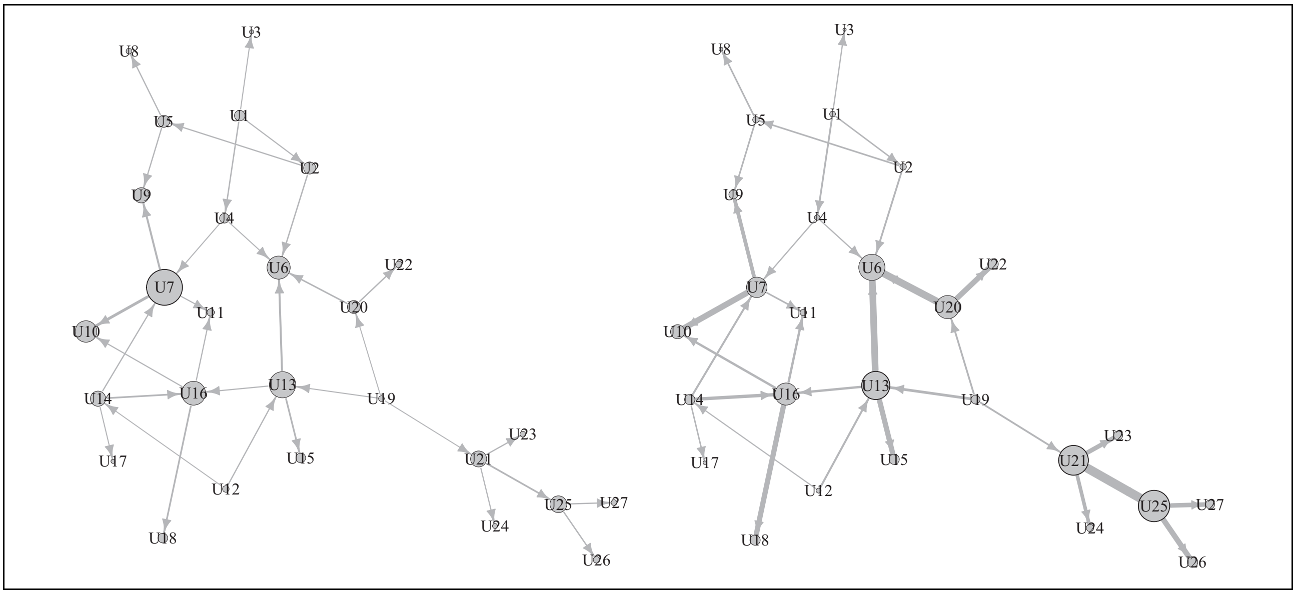

Figure 8. Two weighted and aggregated BoMs. The first (left side) derives from the aggregation of one unit per each end product. The second (right side) derives from the aggregation of a number of units that is based on the described production plan. BoM: bill of materials.

semi-finished products pointing to it), we can deduce that the risk of production rescheduling of such finished or semi-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 replanning will be more restrained.

Properties of the aggregated BoM and their implications

In this section, the centrality measures are analyzed and interpreted in relation to the aggregated BoMs. Hence, to evaluate what the centrality measure means, we must focus on all of the product structures of the portfolio, or its subsets.

The most important implications of the aggregated BoM relate to the overall part number centrality; specifically to the starting materials, assemblies, and subassemblies. 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 in-degree value points out the number of finished products that uses the part (i.e. the assembly, subassembly or starting material). The latter could be taken into consideration when analyzing the impact on production planning and thus determine how to manage the related supply or production. Indeed, the more the part is shared among BoMs, the more the reordering and production planning criteria should be accurately managed.

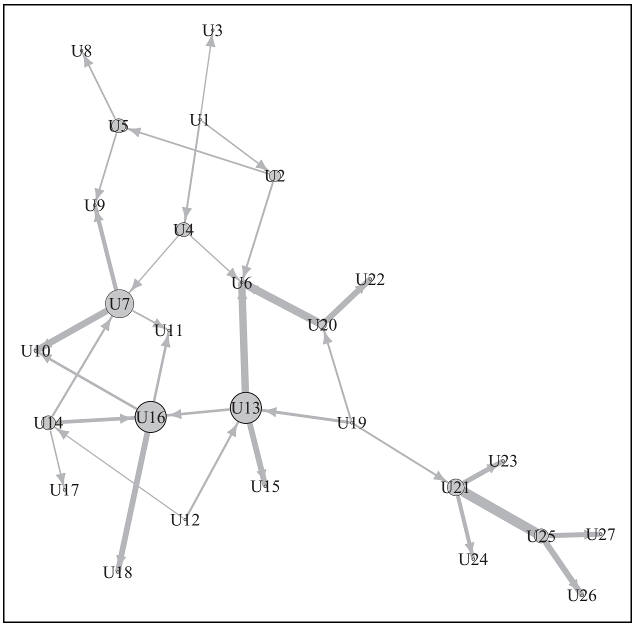

Figure 9. Representation of an aggregated BoM in which the node size is proportional to its betweenness centrality. BoM: bill of materials.

In the left panel of Figure 8, we report the aggregated network in which the strength of the nodes is the sum of their requirements in order to realize one unit of end product. In the right panel of Figure 8, we report the aggregated network in which the strength of the nodes is conversely affected by their requirements in terms of production plan. By comparing the two panels of Figure 8, we observe how the presence of a production plan alters the criticality associated with each node. For instance, when we do not consider the production plan, the node U7 is the most critical, showing a overall strength of $s = 42$ but, when we consider the aggregated BoM, such item is not that critical anymore and the item U25, for instance, can be considered now as the most critical with a value of $s = 180$.

Metrics such as strength and in-degree could be used by inventory controllers and materials managers as inputs for inventory control analysis. Although different criteria are listed in literature to classify parts in material management, strength and in-degree could represent an additional parameter to identify the most critical parts or supplies. The same reasoning could be applied to maintenance optimization processes to identify the most critical spare parts. Within this context, the goal of spare part management is similar to that of material inventory management, which consists of obtaining a clear breakdown of the most frequently used parts to create a cost-effective plan through which to replenish them.

Applying the same metrics to product family aggregated BoMs, the similarity of part sets could be evaluated. Since similarity ratios could help in the application of methods for the rationalization and standardization of components and product structures, the strength and in-degree analysis can support the functional design in order to jointly comply with diversification and cost control needs. To lower the operating costs induced by the strong industrial trend toward products diversification, techniques such as Variety Reduction Program (VRP) can be applied, 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 may help in accurately considering this phenomenon, calculating more precise indexes, and reducing the efforts involved in applying variety control techniques. The impact of the application of these principles is not limited to the simplification of the structure of the products from a design point of view. A more rational structure of the product range corresponds to a reduction in the workload for purchasing and manufacturing processes. This methodology, therefore, gives way to several techniques aiming to reduce the overall operating costs through a rationalization of the product structure.

Conclusions

In this article, we investigated the interrelation between product structure in manufacturing systems and complex networks, assessing the practical implications of the analysis of the BoMs network through centrality measures. We introduced two formal procedures to preprocess BoM data and set the underlying structure that is necessary in order to perform centrality measure analysis. We revealed the possibility of using such metrics to gain insights into the field of operations management. 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 allows one to easily extract information that was previously difficult to obtain.

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

Further development may concern the in-depth analysis of the highlighted implications, possibly by means of data enrichment. Moreover, an overall investigation into the interpretation of a larger set of centrality measures able to provide different meaning of criticality could be undertaken to gain more advantages from the introduced procedures. Doing so could result in ways to support operations management optimization techniques in manufacturing processes, such as modular product design, VRPs, inventory, and production planning optimization. Finally, the interpretation of potential dyadic interactions among specific elements, that is, one to one interactions based on the metadata of nodes, could be of interest when evaluating the information that goes beyond the network structure.

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Supplemental material

Supplementary material for this article is available online.

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