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Procedia CIRP 91 (2020) 796–801

www.elsevier.com/locate/procedia

30th CIRP Design 2020 (CIRP Design 2020)

Assessing the Influence of Generational Variety on Product Family Structures

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Abstract

Increasing market dynamics and shorter product development and product life cycles cause firms to develop new products more and more frequently. To satisfy a high future external market variety with low internal complexity, Design for Variety is carried out for initial structuring of the prospective product family. The influence of new to introduce product features on the product components is estimated in order to assess the future role of the components within the system under consideration. With help of graph theory and the graph visualisation and analysis software Cytoscape, the product components are examined regarding their activeness, passiveness and centrality values. For achieving this, a methodical procedure is presented to set up the applied development framework and to compute effect systems as directed graphs. The product components are then evaluated using a portfolio matrix to identify the impact of the increasing generational variety.

Keywords: New Product Development; Product Generation Development; Complexity Management; Graph Analysis

1. Introduction

Shorter product development cycles and emerging technologies put companies under high innovation pressure while having to deliver low cost and high quality products in global and diversified markets. One possibility to face those challenges is New Product Development (NPD) [16], [17]. To satisfy the diverse market demand and therefore different customers and users, development of modular product families is an adequate strategy [12]. To make the benefits of modular product structuring accessible to firms from the very start, new development of product families need further support as NPD methods traditionally focus single product development [22] while modularisation methods are mostly carried out on grown product families [12]. The early phase of product development is hereby crucial to further product life-cycle activities as critical decisions regarding target markets, utilised technologies and the structuring of the product and its components, in particular the interface definition, are made [17]. However, the necessary information and knowledge to support the decision-making is immature or not available at this development stage [25]. To support insights about components and their relations, the key question, which is dealt with in this contribution, is how components within product family structures are influenced by the introduction of new product features. As the product structure within multiple design domains is understood as a network with elements and links, represented by components and interfaces, these elements are implemented in the network visualisation and analysis software Cytoscape. Different design models are developed within this framework and the product structure as well as the components are analysed regarding future product variety by applying rules of graph theory. Based on a pre-planned external variety offer, the effects of growing variance on components and the product structure are investigated for three future product generations based on data from an industrial project.

2. Complexity in Product Development and Basics of Graph Theory

Product development takes place in an environment that is characterised by the interaction of many different areas and aspects. In addition, the states and boundary conditions of the environment change during running processes [4]. The dynamic change of the environment means that product development, and thus the products developed, are characterised by a certain complexity. It can be beneficial to use the basic definition from cybernetics and differentiate simple, complicated and complex systems in order to achieve a uniform understanding [9]. This distinction has also been introduced to modular product development [12]. Simple systems consist of only few elements and element dependencies. Complicated products are characterised by a high number of interacting elements. If, in addition to the aspects of the complicated system, there is a minimum of dynamics, unpredictability and uncontrollability, the system is

10.1016/j.procir.2020.02.237

referred to as complex [12]. As the product or furthermore the product family can be understood as a system, following the basic definitions above, complicated products are characterized by a high number of interacting elements and complex products show a dynamic change in the parameters of the interactions [15]. Complexity can be divided in external and internal [23]. The main external cause is identified as the market with standards, competitors and customer diversity [15]. Referring to variety management, this is known as the external offer variety needed to satisfy different customers by offering certain differentiating product features. Internal complexity stems from the component and process variety needed to meet those defined properties [12]. This also concerns associated functions and underlying technologies among the product variants and other internal causes like the structure of the organisation and the people involved, as well as processes such as the division of labour in an interdisciplinary content [15]. To estimate how changes propagate throughout the system is a complex topic itself as many components or entities may be influenced by a change and there usually are different alternatives to react to changes [5]. Estimating the impact of changes early on during the development could contribute to identify product areas responsible for future product variety or the decision of module limits. Module decisions, even taking into account different perspectives such as the use of MFD [7] or life phase modularization [12], do not take into account temporal dynamics, which is why the developed product structures have only a very limited validity period.

2.1. Basics of Networks and Graph Theory: Nodes, Paths and Centrality

A graph is a mathematical concept and commonly used as an abstraction for appearances of connectedness of entities and consists of two different quantities [24]. The quantity that is connected, is called nodes or vertices, the connections between the nodes are called edges. Graphs are used for visualisation and analysis of system structures although the underlying data is better created, saved and computed in a corresponding matrix [29]. This adjacency matrix is also a basic component of the Design Structure Matrix (DSM) which has been developed to analyse and optimise modular product structures and still is under continuous extension e.g. in the context of agile product development [10]. In the following, some main definitions from the field of graph theory, necessary for the understanding of the further procedure and analysis, are briefly explained.

A node is the element considered from a domain, represented in the network. The degree of a node describes the number of connected neighbour nodes by an edge. One can distinguish between the active and passive sum of a node. The active sum represents the number of outgoing edges and the passive sum the number of incident edges of the node. Computing the active or passive sum helps identifying the highly connected nodes of the network [6]. The criticality of a node is understood as the product of the active and passive sum and shows the sensitivity towards future adaptions [20]. In graph theory, a distinction between directed graphs and undirected graphs is made [6]. In a directed graph edges have an orientation through a start and an end node. If the node under consideration is a start node, the edge is outgoing and if it is an end node, the edge is incident.

A path represents the connection of two nodes. The connection can be direct or indirect with one or more edges in between. The length of the path is the number of edges of the path [6]. Identification and computation of specific paths in networks such as the shortest and longest path requires algorithmic support [1]. The shortest path is the minimal number of edges connecting two nodes. The longest path is the maximal number of edges connection two nodes while passing a third node only once. The average path length describes the whole network and is the arithmetic mean of paths connecting every set of nodes in the network [18]. In dynamic networks representing a system, a path illustrates a sequence of influences and showing far-reaching dependencies that are often hardly considered if they are not visually analysed [15].

The centrality of a node based on closeness is computed by summing the distance or path length from that node to all other nodes. Forming the reciprocal of that value forms a measure of closeness. Centrality based on betweenness is the number of shortest paths between every pair of nodes that cross the node under consideration. This value identifies nodes which are highly integrated in sequences of influences [8]. The value of the centrality based on betweenness is normalized thus values are between zero and one. If normalisation is not possible, because the graph has multiple edges between a pair of nodes, the value is called stress centrality [3].

2.2. Effect System as Directed Graphs

Due to the non-deterministic behaviour of complex systems the ununderstood complexity is often ignored [30]. The system-oriented or networked thinking, both oriented from the general systems theory and cybernetics, describe different approaches that methodically attempt to cope with complex systems. The sensitivity model approach by Vester emerged from bio-cybernetics [27]. Since the complete complexity of a system can never be captured or mapped, the procedure is based on the reduction of the represented complexity by a set of manageable, system-relevant variables, the detection of dependencies and the identification of general behavioural patterns [30].

By the graphical visualisation of the dependencies of the variables and query of each possible influence of the elements in the system the effect system consisting of only directed influence is derived [31]. The directed influences are key to identify the roles of each element in the system because the active and passive sum can be computed [30]. Elements can take an active, a passive, a critical or a damping role. Elements in the lower right sector are passive as they are influenced with a greater degree than they influence other elements. In contrast active elements in the upper left sector influence more elements than they are affected by. Elements that are sparsely affected and have little influence are damping and in the lower left sector. Critical elements are situated in the upper right corner as they have high influence and are highly influenced. Vester proposes according to the position in the portfolio different potentials of the system elements. With active elements, in contrast to passive elements which have low impact, the system can be changed permanently. Critical elements can change the system permanently as well, but the effect on the system can be uncontrollably as these elements can be highly influenced by a feedback of their own influence. Elements in the damping sector have little to no potential regarding any effect on the system [30].

2.3. Product Structures as a Basis for Network Analyses

To reduce the internal product and process complexity while handling the external complexity which stems from a broad variety of product variants offered to different customers, the Integrated PKT-Approach for Development of Modular Product Families has been developed [12]. The main activities are the analysis of the external and internal variety to reduce the internal variety with help of Design for Variety (DfV) [11] and the subsequent technical-functional and product-strategic lifephase modularisation [2], [12]. The most important steps of DfV are explained since they are needed in the following. The core model for DfV is the Variety Allocation Model (VAM) [12]. It consists of the four levels, customer relevant, distinguishing product properties, variant function, variant active principles and variant components, whereas each level is supported by design tools. The elements from each level are connected and the correlation of the external offer variety of a company and the necessary internal component variety for the product family under investigation are opposed and can be analysed and optimised within the VAM [11], [12].

For NPD of modular product families the steps of DfV steps can be initially run through [13]. A modular product structure is derived within the evolving product architecture and further support for the juvenile components in the early phase is achieved by introducing the Product Family Interface Graph (PFIG) as an additional product development tool [14]. An example of the PFIG is shown in Fig. 3 which is object of the network analysis later on. It consists of abstract components and information about their linkage to represent the product structure with regard to variety. While Kipp mainly considers variant aspects of the product family during DfV [11], standard parts are essential within initial development activities [13]. A third dimension of variety is introduced by additionally distinguishing into specific design parts to reach more flexibility and uniqueness through customisation in highly differentiated and dynamic markets [13]. The discretion of time-steps within DfV to support the development of future product generations based on a fixed external variety is already shown in an extended VAM by Küchenhof [13]. For further network analysis, the time-discrete PFIG is implemented in the network visualisation and analysis software Cytoscape.

2.4. Cytoscape

Cytoscape is an open source program designed for visualising molecular interaction networks [26]. Although the program is used primarily in the field of biological research it can be used to visualise and analyse any network which is represented by edges and nodes [26]. The possibility of arbitrary extensibility through plug-ins to extend the program functionality [19] is one reason why Cytoscape was chosen as the visualisation software. The data of the visualisations was obtained from an excel data sheet and directly loaded to Cytoscape where little processing was needed to acquire the networks. Basic graph analysis features and visualisation algorithms come with the core program and for the scope of the graph analysis presented in this paper there was no need to write a plug-in for specialized graph analysis or visualisation. Cytoscape enables to give elements different shapes according to their domains and colour the nodes and edges corresponding to an attribute or parameter. Network filters can be applied to focus on certain subsets of networks for independent analyses. For further analysis it is possible to visualise and analyse dynamic network data with Cytoscape build-in features and plug-in extensions [19].

3. Methodical Procedure

The procedure is explained in the following and can be comprehended in Fig. 1. The main idea is to analyse a product structure with respect to variation over time. The system under consideration is defined in the first step. In order to do that, adequate domains need to be selected. Leaning on DfV after Kipp, the domains considered represent the different levels of the VAM as can be comprehended in Fig. 2 (purple frame). The diagonal entries represent DSMs for each domain with the product component DSM on the lowest level, which describes the product family structure and variance in terms of its components and linkages and is framed yellow in Fig. 2. In step 2, dependencies need to be identified and interactions are recorded in the matrices. The inter-domain dependencies, connecting the MDMs are denoted by solid lines in Fig. 2. The consideration of trends to represent market dynamics is planned as a part of future studies and denoted by dashed lines as is the comparison of structural alternatives within the DSM domain. The domains trends and features, inhibiting external complexity, encompass the internal domains and are marked with a grey background in Fig. 2. The effect system of components is computed in step 4. Calculating the active and passive sum, as well as centrality values of the components, the results are plotted in the portfolio matrix in step 4 to assess the future role of the product components within the system.

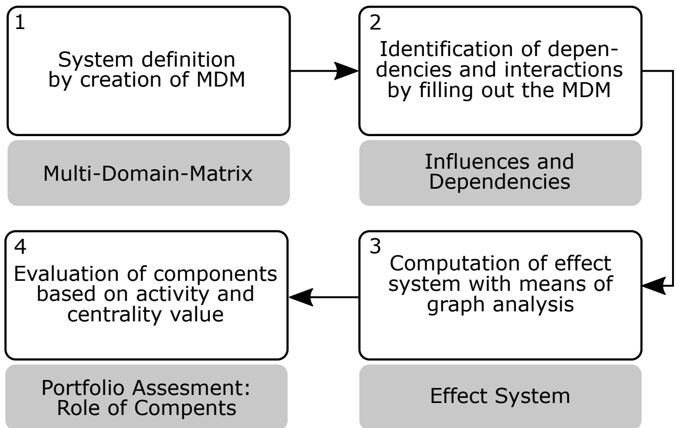

Fig. 1. Flowchart of the methodical procedure

3.1. Deriving the Product Family Interface Graph

The regarded product structure represents a generic evolving cyber-physical system in the market of new generation products in the field of liquid to aerosol applications. Due to non-disclosure agreements and proprietary contents, not all information of the real development case can be displayed or must be abstracted. The future product family generations are derived within the implemented multi-domain network on DSM level visualised in the PFIG as can be seen in Fig. 3. The PFIG represents the product structure in terms of components and its

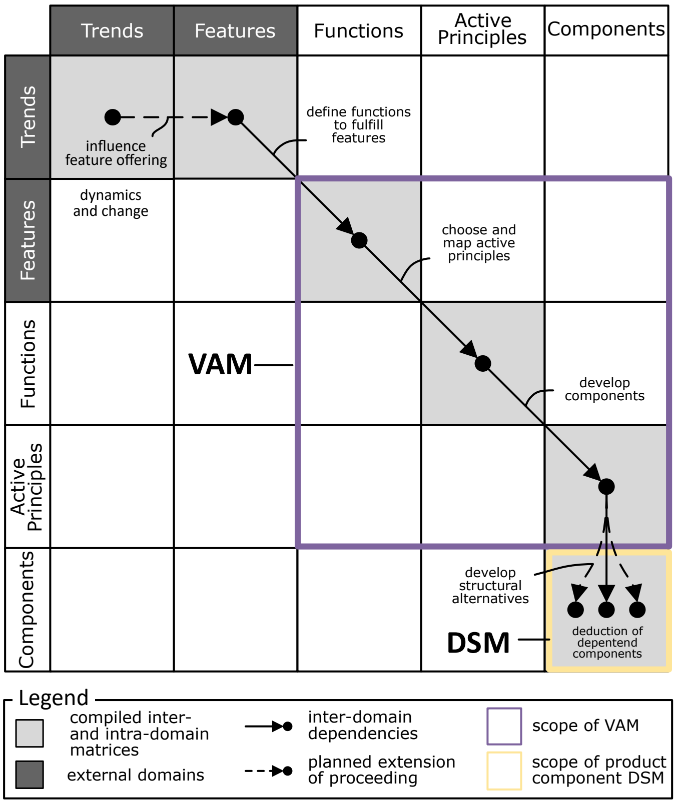

Fig. 2. Linkage of intra- and inter-domain matrices considered

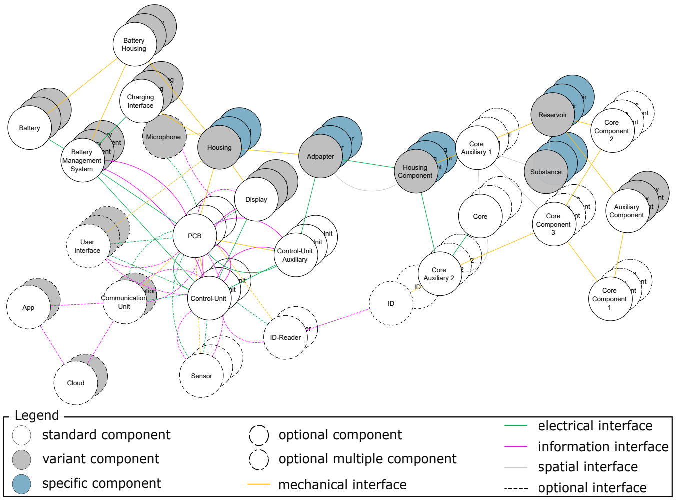

Fig. 3. Generic product structure with mechanical, spatial, electrical and information interfaces (PFIG) implemented in Cytoscape for time-steps T1, T2 and T3

linkages and can be understood as an undirected graph since the presented interfaces give no information about directed influence. The linkages between the elements represent the product component interfaces such as mechanical (yellow), electrical, (green), information (magenta) and spatial (grey) interfaces. Optional elements, that can be present in one product variant, but not in the other, are indicated by dashed lines (concerning components and interfaces).
In order to observe the influence of the individual components, a directed graph must be created. Therefore, some additional information with respect to growing product variety is expressed in the elements. The white colour indicates standard components which are used as identical parts in the whole product family. The grey colour shows scalable or parametrisable components (e.g. different length or colour), while blue elements indicate customer specific components that allow individual component changes. Each of the three product generations and corresponding product structures are represented in successive layers; the increasing product variety can be observed by the changing colours of the components in each plotted time-step. By the discretion of time-steps, the dynamics of each component can be traced and a direction of activity on other components can be pictured. Thus, effect systems exhibit information that a static model such as a DSM or the PFIG can not give and is developed in the next step.

3.2. Creation of the Effect Structure

To examine the influence of growing product variety for the considered product components and generations, an effect structure for each time step has to be created independently. The initial situation ”T0” which is considered as the minimal viable product with only standard components is not illustrated. The effect system originates from the introduction of new features in each time step, considered as product generations with increasing variety over time. The created effect systems for the time steps ”T1” to ”T3” can be seen in Fig. 4. In the effect systems only components affected directly or indirectly by the introduction of new features are shown. As only directed dependencies are noted and the dependencies are not inevitably dependent on structural interfaces within the product, the structure of the effect system can differ from the PFIG. The identification of the influenced components and its impact on others is best discussed in a group as the view on dependency can be subjective. The three effect systems show a different intensity of dependencies in each time step. The second product generations offers a multitude of product features compared to the previous generation. A closer examination of the dependencies, such as the outgoing dependencies of the display component in ”T2” and ”T3”, shows how a different feature introduction in each generation can result in other directly influenced components.

3.3. Assessing the Role of Components

The active and passive sum of the components are calculated independently in each time step and then accumulated and plotted into the portfolio diagram (see Fig. 5). The passive sum of the components is located on the x-axis and the active sum is located on the y-axis. Each component is represented by a circle whereas the size of the circles differs, indicating the stress centrality value. Here, stress as a measure for centrality of the components is used, as the effect systems differ from each other and the normalised values of the betweenness centrality can not be used for comparison. As for the active and passive sum, Cytoscape was used to calculate the stress centrality value of the components. The increase of the circle size represents the gain of stress according to the stress value in each product generation and indicates how much a component is influenced by changes derived from the introduction of a feature. Variety of components differs in the three generations, indicated by the colouring of the outer rings according to the level of variety. The components Housing and Reservoir are highly influenced indirectly as shown by a high stress centrality value in each time step. They

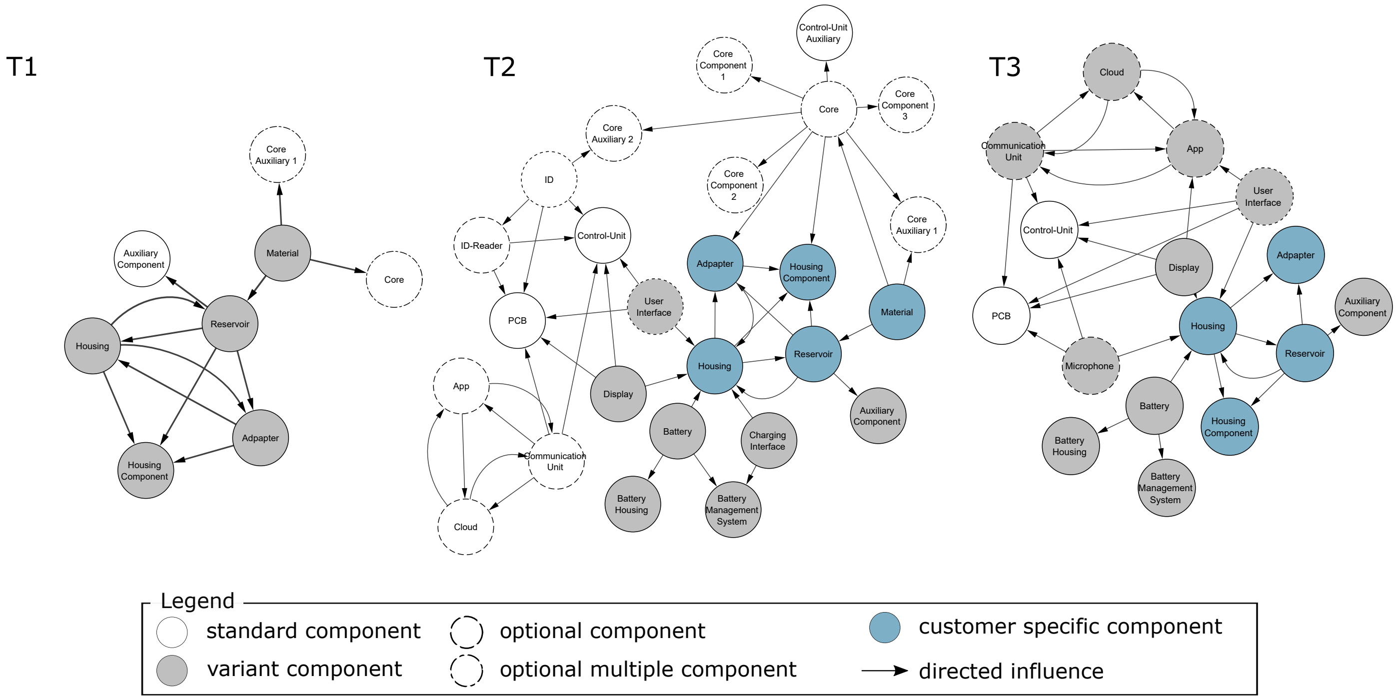

Fig. 4. Effect systems of product components for three time-steps T1, T2, T3 representing product generations visualised in Cytoscape

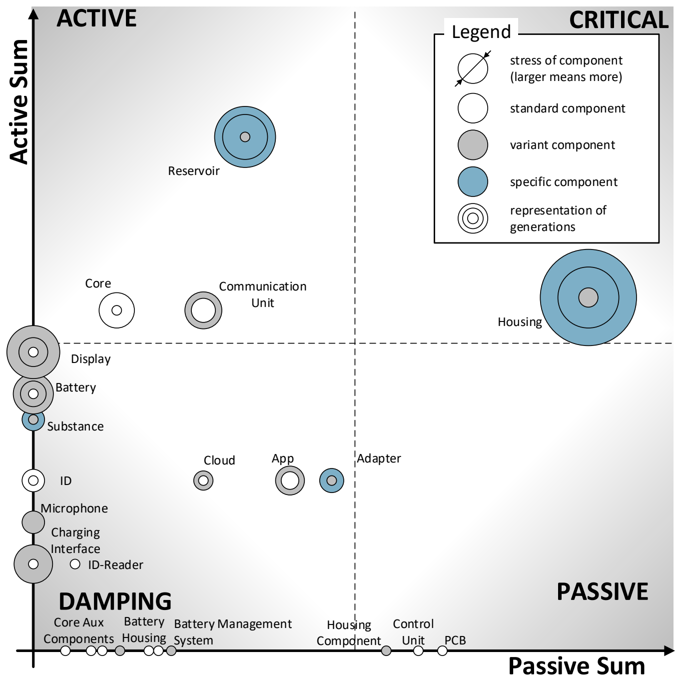

Fig. 5. Portfolio of activeness, passiveness and stress of components

switch from variant to custom which is in favour of customisability. The Housing is as well directly influenced highly by other components as the high passive indicates. The Reservoir has a higher active sum as it is a driving sales factor regarding offer variety. The Core has a moderate active sum and a low passive sum. Although the Core remains a standard component it is influenced by the extended variety offer as can be seen in ”T2” in Fig. 4. Here an optional second Core unit could be implemented to offer performance variety.

The Display and Battery both have a medium active sum which is slightly higher compared to the active sum of the Substance. The high stress centrality value indicates far-reaching influences from these components. The components Control Unit and the PCB stand out with a high passive sum and no active sum and thus serve as enabling elements. On the vertical axis, components with a passive sum equals zero are situated. They are mainly variant components and part of the offer variety. Components on the vertical axis with an active sum equal to zero are mainly standard components. Components that are responsible for product variety exhibit a high active sum and thus influence other components within the subsequent product generations. Passive components on the contrary are strongly influenced by the creation of the external variance by active components and therefore serve to keep the internal variety low and are possible candidates for standard components levering commonality. As only components on a path in the effect structure are considered in the calculation of the stress value, start- and end-nodes are not affected although they are part of the path. Thus components on the horizontal axis have a stress centrality value equal to zero as they are always end nodes. Here different graph analysis algorithms have to be deployed to assess the indirect influence.

4. Conclusion and Outlook

The early phase of product development is characterised by high dynamics and uncertainty. Thus, a better understanding of the interacting components within complex systems is needed. The presented approach shows how an effect system based on a product structure with increasing generational variety can be derived based on a changing external offer variety. The system dynamics is represented by the introduction of new product features and subsequent product component variety, which is simulated for three time-steps. The growing network is implemented, visualised and analysed with help of the graph visualisation and analysis software Cytoscape. Unlike a static product structure, the presented effect system consists of directed edges. This major difference helps assessing the role of product components within the development of product generations and furthermore enables the application of a plurality of methods of graph theory. The active and passive sum and the stress centrality of the product components were computed. The active and passive sum indicate the direct influence whereas the indirect influence on the components is shown by the stress centrality value. As a next step, product structure alternatives can be analysed to examine the impact of interface changes as an addition to increasing product variety as the main influencing factor. As a large impact on the product architecture arises from external drivers of change such as new trends, emerging technologies, regularities and patents, these should further be considered to complement the method.

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