Exploration of multi-layers networks to elicit and capture product changes

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Abstract. Change management is a key process in the Product Development Process. In a context of availability of large data on the process through Enterprise Information Systems like PDM (Product Data Management) or PLM (Product Lifecycle Management) systems, the structured data network can be analysed to identify key feature to improve the process performance.
In this work, we propose a multi-layer network to engineering change management that models product, organisation and change facets together. Once build, this network is analysed with some classical graph tools to identify some key features allowing to elicit some organisational behaviours. This approach is applied on two pedagogic examples.

Keywords: Engineering change · multi-layer network · product development process · PDM.

1 Introduction

Changes are classical during the Product Development Process (PDP) and the importance of managing design change is accordingly well-recognised by practitioners and researchers [6]. In a context of strong digitalisation of the PDP with the support of recognised information systems like PDM (Product Data Management) and PLM (Product Lifecycle Management), change can be tracked at each stage through ECM (Engineering Change Management) process [13].

Nevertheless, ECM can be still improved and one aspect that has been less analysed is the relation between the product structure, the organisation and the change management. In particular, some can be interested to analyse the traces of changes through all data and information stored in PDM from previous PDP. By nature, all these data are structured and interconnected, and in this research work, we would like to explore the created data network to elicit and capture some key features that could explain the efficiency (or not) of the change management.

In this work, due to the large diversity of semantics existing in a PDM, we explore more precisely the concept of a multi-layer network [8], [11], [1].

Paraphrasing [11], a standard graph is often described by a tuple $G = (V, E)$ where V defines a set of vertices and E defines a set of edges (vertex pairs), such that $E \subseteq V \times V$. An intuitive definition of a multi-layer network first consists in specifying which layers nodes belong to. Because we allow a node $v \in V$ to be part of some layers and not to others, we may consider 'multi-layer graph' nodes as pairs $V_M \subseteq V \times L$ where L is the set of considered layers. Edges $E_M \subseteq V_M \times V_M$ then connect pairs $(v, l), (v', l')$. An edge is often said to be intra- or inter-layer depending on whether $l = l'$ or $l \neq l'$.

More precisely, we propose a multi-layer network for change management that models product, organisation and change facets together. Once build, this network is analysed with some classical graph tools to identify some key features.

The outline is as follows. Section 2 reviews the literature on change management with a network modelling approach. Section 3 presents the proposed multi-layered network approach and section 4 presents an application on two pedagogic use cases. Section 5 concludes and presents some perspectives.

2 Literature review

Authors of [2] provide a thematic analysis of state-of-the-art in design Change Propagation Analysis (CPA), and highlights opportunities for further work. In particular, they identifies seven use cases for CPA in the literature: CPA can support the generation of alternatives for implementing a change, the assessment of how a proposed change might impact a design, the assessment of how a proposed change might impact a product family, the assessment of a proposed change in terms of redesign cost, time and effort, the assessment of how a proposed change might impact production, the coordination of change activity and the improvement of designs with respect to potential future changes. The last two use cases cover our research questions.

Authors of [5] focus initially on the analysis of the causes of the change propagation and its management by the company: it then proposes design solutions in order to limit the impact of the propagation of changes. It also proposes a classification of the components of a product with respect to their character to transmit or not the changes during the propagation:

- "Absorbers": components that "stop" changes more than they involve other parts,
- "Carriers": components which transfer changes from one part to another (as many changes induced by the component as changes applied to the component),
- "Multipliers": components that pass on more changes than they receive from other parts.

If a large literature on engineering change management focus on the product itself only and specific approaches like DSM (Design Structure Matrix) [15] [10], some explore this concept through a network vision [9]. Among the literature using a network approach, the CPM method (Change Propagation Model) [4] aims at predicting the propagation of changes within a complex product. This method is built using a network model and is based on 2 values evaluated by experts between the components directly in contact (mechanical, information or energy transfer) in the product in order to eventually calculate the image of these values for each pair of components of the product: the analysis, in the long run, thus allows to highlight the central components and those having a remote impact in the potential cascades of changes.

Based on these two root papers on the subject, others apply tools to analyse the network models defined through the CPM method, like [3] or [14].

Some authors explore multi-layered models for this context. For instance, in [7], the nodes are changes that have been proposed in the past on the product and the links are directed and unweighted to represent the relationship of parentage between the changes, i.e. a link is created from a source change to another target if this source change has propagated and generated this target change. The study is therefore based on real cascades of changes that have operated on the product. Attributes are also added to the nodes to identify which of the past changes were retained and actually made and which were rejected: some of the analysis tools used will focus only on the changes made. A study of the patterns of change propagation is also carried out in order to better understand how this phenomenon works. From this, several new tools could be developed:

- CPI (Change Propagation Index): is an index between -1 and 1 which allows to judge the category of a component according to [5] with the help of the number of changes undergone and transmitted by the component.
- The PDSM (Propagation Design Structure Matrix) and CPFM (Change Propagation Frequency Matrix): which refer respectively to the number and frequency of changes induced by one component on another. The frequency of changes is the ratio between the number of changes transmitted by the source component to the target component and the number of changes applied to the source component. Only completed changes are taken into account in this study.
- the CAI (Change Acceptance Index) and the CRI (Change Reflexion Index): 2 complementary indices which make it possible to evaluate the openness or obstinacy of a component to changes via the study of the attributes (retained or rejected) of the changes applied to the component.

Differently, the approach in [12] is based on 3 distinct layers: one relating to the product, one relating to the changes and one relating to the social organisation of the various actors gravitating around the design/re-design of the product. It should be noted, however, that in this study the links in the product layer are directed but not weighted as they were in the vast majority of previous studies. In this last so-called social layer, the nodes are people or groups of people and the links between them represent the existence of a communication link: these links are considered to be undirected and unweighted. This model has the advantage of being compatible with many of the tools presented previously but also allows new ones to be developed:

- PAR (Proposal Acceptance Rate): this is an index similar to the CAI; here we calculate the rate of acceptance of changes proposed by a node of the social layer, i.e. a person or a group of persons.
- The extension of the PDSM and CPFM matrices as well as the CPI index to the nodes of the social layer (as these tools, defined by Griffin (2009), were therefore only applied to the product network and using the information extracted from the change network).
- Propagation Directness (PD): this measure corresponds to the shortest path between 2 components of the product layer between which changes have propagated. As the links in the product layer are unweighted here, we can see whether the propagation is direct ($PD = 1$) or indirect ($PD > 1$) and judge the distance if the propagation is indirect.

In conclusion, the analysis of these different studies highlights several key points:

- Many efficient tools have already been developed and it seems interesting to try to build a network adapted to these tools in order to be able to re-use them, with some modifications if necessary.
- The construction of network models relies heavily on expert opinion in the choice of nodes and weights: it seems interesting to try to limit this component by proposing a construction protocol based on a medium containing the required data such as a PLM.
- The social dimension has been neglected in many articles: it seems interesting to keep this dimension in the study as it is one of the causes of the propagation of change.
- A network associated with past changes seems to be a very powerful tool if many changes are implemented in the network: it allows us to observe real cascades of changes in order to base the study on something other than a simple prediction model, and it therefore also allows us to question prediction tools by comparing the results of these tools with known data on past changes

Finally, it is a multi-layer network which will be retained in order to be able to preserve the study of the social organisation and past changes and this by trying to build a model making it possible to preserve the possibility of using the most powerful tools of analysis met in all these articles.

3 Proposition

In this section, the multi-layer network model is described, composed by several layers all linked together (Fig. 1):

- a set of layers associated to the hierarchical description of the product,
- two layers associated to the social organisation: "People" and "Teams".
- a last layer associated to changes.

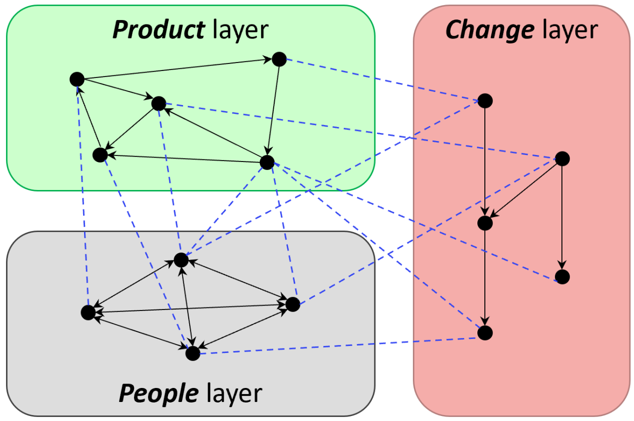

Fig. 1. A simplified representation of the multi-layer network, with only three layers. The dark edges are intra-layer edges, the blue dashed ones are the inter-layers ones.

3.1 Definition of layers and intra-layer edges

Product layers The product layers are based on the EBOM (Engineering Bill Of Material), closely to the product model structure proposed by [4]. More precisely, there are as many layers in the network as there are levels in the EBOM and the vertices in these layers correspond to articles in the EBOM (i.e. components of the product).

In a given layer, the edges represent the dependencies of change propagation that may exist (e.g. function/requirement sharing, kinematics joints, etc.). More precisely, an edge is created from vertex j to vertex i if, when component j is modified, this change may imply a significant change on component i. These edges are therefore oriented but also weighted by a number ranging from 0 to 1: the higher the weighting, the stronger the dependency between the components. The weighting, called risk of change and noted $r_{i,j}$, is defined as $r_{i,j} = l_{i,j} \times i_{i,j}$, where:

- $l_{i,j}$ represents the probability of propagation of the change from component j to component i,
- $i_{i,j}$ represents the impact rate of the change induced on i by j if the change has effectively propagated from j to i.

Organisation layers These layers are associated with the social organisation of those who design the product. It can be seen as an evolution of the "Social" layer of [12].

More precisely, two layers are defined: "People" where each vertex represents a person in that organisation, ad "Team" where each vertex represents a group of several people. These layers both exist since some changes are initiated by people and some by groups

A link between 2 nodes represents the existence of communication between the 2 persons or teams represented. These links are unweighted and non-oriented because it is assumed that if communication exists between 2 people, then it exists in both directions: each person can provide and also receive information from a person with whom they are in contact. Generally speaking, this kind of links can be e-mail conversation, chat discussion or informal meetings but it is very difficult to capture these. So in this environment, we will first focus on empirical evaluation between teams (based on expert evaluation) and on requests between two people existing in a PLM framework.

Change layer This layer refers to the changes already made or proposed during the design/re-design of the product under study: each vertex represents one of these changes. This layer is inspired by the change network model of [7]. An attribute is associated with each node according to whether the change it represents has been retained or not (held, rejected or under consideration).

The edges in this layer represent the relationship between 2 changes: if a change 1 propagates from a component i (where it is applied) to a component j, then a change 2 associated with the propagated change on j is created in the "Change" layer and thus a link is created from vertex 1 to vertex 2. These links are oriented and unweighted.

Finally, we create a binary attribute which identifies whether the cascade of changes of which the node is a part is complete or not. It is automatically assumed that "Retained" changes have a complete cascade, but it may happen that a "Under consideration" change cascade is complete or unfinished, as a "Rejected" change cascade was after the change cascade was completed or not.

3.2 Definition of inter-layers edges

A first set of inter-layers edges represent inclusion:

- an edge between two vertices belonging to two different product layers represents a EBOM link,
- an edge between a vertex in "People" layer and another in "Teams" layer means that a person belongs to a team.

The edges between Product and Change layers mean that a change is applied to a given product component. It should be noted that not all changes are necessarily associated with a component: indeed, a system engineer (or respectively an engineer in charge of calculations) may propose a change following a modification of a requirement (or respectively following a calculation which calls into question the satisfaction of a requirement) which is not directly associated with a component but which will create child changes, most probably by other engineers, which will be relative to the product components.

Finally, an edge between a vertex of an Organisation layer and a vertex of the Change layer means that a people or a team has participated to this change at a phase of its lifecycle, whereas an edge between a vertex of an Organisation layer and a vertex of a Product layer means that a people (or a team has contributed on this component.

It should be noted that all inter-layers edges are non-oriented and non-weighted, due to their intrinsic nature.

3.3 Network analysis tools

Based on the literature review, we propose to explore several tools to analyse the network and its internal information (see [7] and [12] for more details):

- The degree, which is a measure of centrality for a node, applied on one type of link at a time,
- PDSM (Propagation Design Structure Matrix) and CPFM (Change Propagation Frequency Matrix), which analyse change propagation inside a layer (i.e. inter-layers edges between change layer and another one),
- Component categorisation indices (CPI - Change Propagation Index, DCPI - Degree Change Propagation Index, LCPI - L-Change Propagation Index), to classify a component in between “Absorber”, “Carrier” or “Multiplier” [5],
- PAR (Proposal Acceptance Rate) that evaluate performance of a vertex from an organisation layer according to change proposition,
- CAI (Change Acceptance Index) and CRI (Change Reflexion Index) that evaluate performance of a vertex from a product layer according to change acceptation.

4 Application on two use cases

In order to validate the completeness of the proposed approach and to estimate the quality of the analysis that can be made on it, the approach has been deployed on two pedagogic use cases: an office chair (composed of 10 components, 7 changes and 4 engineers from 2 teams, Fig. 2) and a bike (composed of 28 components, 7 changes and 6 engineers - no associated team, Fig. 3).

The office chair example, by its small number of edges, allow to manually explore the model and calculate all tools. For instance in Tab.1, we can identify from DPCI that the seat is a “Multiplier”, which is expected for a central part of the chair. Still with this example, the wheels are also a “Multiplier” due to the strong asymmetry in the relation with the leg extension: the weight of the (Wheels → Leg extension) edge is three times bigger than the (Leg extension → Wheels) one.

The bike example, with an increased complexity, allow us to perform some sensibility analysis on the different tools. For instance, by modifying the weight of the intra-product layer edges between the bike fork and the components in contact by 20% (increase for incoming edges and decrease for outgoing edges), this component change from a carrier behaviour to an absorber one. This behaviour change is easily identified with the degree. Moreover, the DCPI analysis

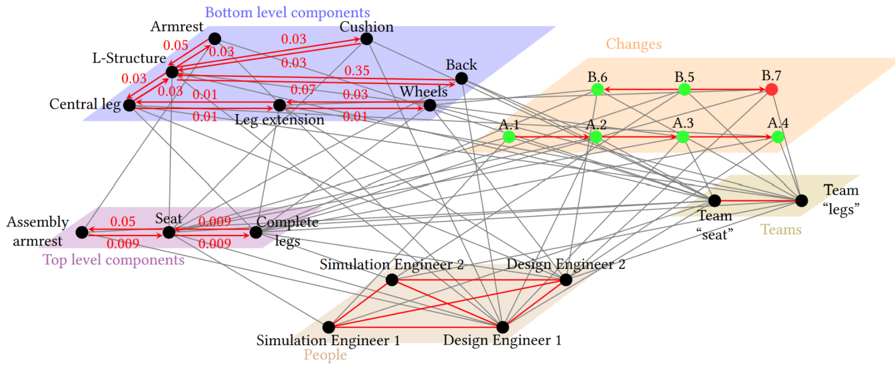

Fig. 2. Representation of the network associated to the office chair, with 2 product layers defined

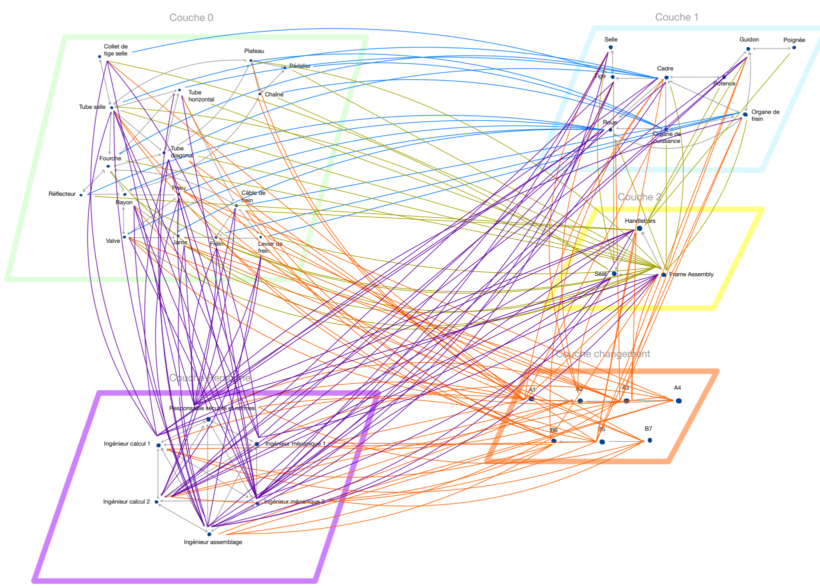

Fig. 3. Representation of the network associated to the bike, with 3 product layers and only the people layer defined

		Incoming Degree	Outgoing Degree	DPCI
Bottom level Comp.	L-Structure	0.46	0.16	-0.48
	Cushion	0.03	0.03	0
	Back	0.07	0.35	0.67
	Armrest	0.03	0.05	0.25
	Central leg	0.04	0.04	0
	Leg extension	0.04	0.02	-0.33
	Wheels	0.01	0.03	0.5
Top level Comp.	Seat	0.018	0.059	0.53
	Armrest Assembly	0.05	0.009	-0.69
	Complete legs	0.009	0.009	0

Table 1. Determination of degrees and DPCI for edges from intra-product layers on the office chair example.

highlights the impacts on the other components, with an increase of the change propagation inside the bike with this example.

With these two examples, we can conclude on the relevance of this approach to explore the relations between the product and the organisation in the context of change management. Some nodes, either in the product or in the organisation, are central to some change propagation and so require a initial attention to ensure that the initial choices are consistent and will not provide too much loops in the future. The next step is now to directly implement this multi-layer network approach on data and information stored inside a PDM tool on existing product development, to better understand and navigate on these relations between organisation and product and so potentially find improvements for future product development projects.

5 Conclusions and perspectives

Engineering change management is a strong research domain, with a large literature on tracking, visualisation and prediction of changes and their impacts. Nevertheless, the relations between the product structure, the organisation and the change management have been less analysed, in particular with the objective to improve the overall PDP. This issue can be more easily tackled nowadays with the strong digitalisation of the PDP and as a consequence the access to a large number of structured data and information in this context.

This article explores the use of a multi-layer network with graph analysis tools to elicit some structural and organisational behaviours. This multi-layer network models the product structure, the organisation and the changes together. The application of this approach on two pedagogic examples seems promising for future works.

The underlying graph that exists in any Enterprise Information Systems and which is developed during the PDP is an implicit representation of the organisation implied in the PDP and the analysis of this graph (completed with some external information to capture) can be a strong source of factual knowledge to help organisation behaviour improvements. It factually highlights the converging points of product and organisation, which should be monitored to ensure the fluidity of the PDP.

For the future, the application on more examples coming from real PDP and extracted from PDM systems is the first perspective, in order to really tackle the links with the organisational behaviour. On the other hand, changes are dynamic by nature and the evolution of these networks during the PDP life should be examined to better elicit some key features.

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