Modelling Efficient Product Development Systems as Network-of-Networks

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***Abstract*— Whilst Product Development is the basis of engineering, increasingly complex products has a tendency to also increase the complexity of the Product Development process, and in many cases the process is not truly understood. There are many tools that have been developed for managing complexity, but few that are specific to Product Development and fewer still that provide pragmatic analyzes that can be used by decision-makers. This paper develops a methodology to apply a Network of Networks approach to data collected from a Product Development organization and provides an accompanying pragmatic analytic framework that can be used by decision-makers on all levels. It then uses an Agent-Based modelling approach to represent the knowledge diffusion within Product Development. This allows a microscopic analysis to complement the macroscopic analysis of the Network-of-Networks approach. This will allow an organization to analyze its current practices on both macro and micro scales, model dynamic changes to the structure of the organization and understand its internal dynamics, with respect to development teams and the design process. This will illuminate the complex system dynamics in Product Development that would otherwise be viewed of as unexpected consequences to a system intervention. This understanding will give greater ability to make suitable, risk-mitigating decisions.**

Product development; Network-of-Networks; Requirements modelling

I. INTRODUCTION

A key challenge in Product Development is enabling decision-makers to understand the cause and effect of events in the process. Product Development consists of tasks and events that are embedded in people and processes, which in turn are embedded in the wider organizational and sectoral frameworks. Whilst there is a lot of literature that analyzes specific aspects of successful Product Development organizations, there are few that comprehensively provide a framework that manages its complexity.

In many Product Development projects there is a strong desire to reduce the cost of the product and reduce the time to launch. A series of decisions that have to be made by many different decision-makers is implicit in this process. However, the impact of these decisions are too complex to be documented and understood. This makes it particularly difficult to allocate resources and to draw up budgets. There is an undergoing study to understand the natural progression of Product Development in order to improve decision-making ability and to understand the inherent processes in order to improve them.

As such, this paper aims to provide two things. Firstly, an overview of the literature relevant to managing complexity, in order to develop a lens through which a complex Product Development process can be viewed. This will illuminate the core dynamics of the Product Development process. Secondly, create a useful decision-making framework that enables optimized and risk mitigating decisions in different innovation systems. This paper is structured as follows: section II defines the scope of the analysis and explores some of the existing literature. Section III defines the methodology and explains the rationale behind model's features. Section IV provides the analytic framework that will provide pragmatic insight from the created model. Section V provides the conclusion and outlines the current and further work.

II. BACKGROUND THEORY

A. *Innovating Organizations*

Whilst managing complexity is vital in making decisions, it is important to understand the type of Product Development organization that is being investigated. Different types of organizations face different challenges and goals; typically, it comes down to the innovation challenges that an organization's strategies have created. As per Foster's S-curve [1], radical innovations are typically fostered by organizations with high Research & Development spending. In traditional management and strategy of innovation literature, radical innovations are fostered by 'organic' Product Development processes [2]. Many papers have identified several characteristics of successful 'innovating' organizations. Typically, cross-functionality, strong communication, decisive and supportive leadership, connectivity (a.k.a. gatekeepers), team composition etc., are considered vital [3-5]. Companies such as IDEO also advocate mobility and collaboration between as many people from different backgrounds as possible [5].

Industries competing in consolidated designs typically need to focus on process innovation, in order to differentiate on cost whilst only being able to incrementally improve the technology's performance [2]. In traditional management and strategy of innovation literature, this involves taking a 'mechanistic' approach at the risk of creating a competence and resource lock-in [2]. Whilst applying techniques such as "Lean" to the Product Development process has found some success [6-9], there are significant drawbacks (loss of skill in the workforce, generation of "useless" data that cannot be referred to in the future, technological lock-in, etc.).

However, without differentiating in cost, there is a tendency to be quickly overtaken by competitors.

Observation 1: Product Development systems are characterized by different forms of innovation. These need to be understood and applied as a paradigm during analysis.

B. Modelling Complexity

Product Development can be characterized by a series of people, tasks, data and information. As such, it is possible to deal with the complexity by modelling it. Dealing with complexity in a systematic way is paramount to Product Development's strategic and management approach. Epstein (2008) [10] states that whilst system prediction is implicit in modelling, it only shows part of the benefits and he identifies 16 other reasons to model.

The most relevant of these at this stage are to:

- Explain the phenomena in the system
- Guide data collection for the system
- Illuminate core dynamics of the system
- Demonstrate tradeoffs / suggest efficiencies in the system

It is important to clarify early how a proposed model should be used and what the limitations are. Critics such as Wiig [11] justifiably question whether one can systematically and rigorously model processes that are considered to be 'black-box'. However, this simply highlights the importance of using models as tools to be used and not as standalone solutions [10].

It is the purpose of the model to provide information that can then be used by stakeholders to make more informed decisions (know-what, know-why, know-who, know-where, know-when) [12] and analyze the system interactions and outputs to propose a grounded action.

Observation 2: Models provide many benefits aside from predictions. Modelling Product Development could adequately provide a tool to manage its complexity and to aid in its analysis.

C. Network-of-Networks

Networks are defined by Nodes (that can be defined by persons, objects, artefacts, etc.) and Edges (connective property between nodes). The flexibility of the networks' approach lies within the ability to completely define what the nodes and edges are. As such, a multitude of different complex networks have been studied (e.g. the World Wide Web, biological cells, Bose-Einstein Condensates, the spread of new ideas or innovations) [13].

In the context of Product Development, people contributing to the process are an obvious choice for nodes. However, tasks, events, requirements, designs and prototypes could all be considered as well. Indeed, the process to come out with a design is much more complex than just the human interaction with one another. Maurer [14] identifies that Product Development complexity arises from Market complexity, Product complexity, Organizational complexity and Process complexity. He deals with this complexity by taking a Multiple Domain Matrix (MDM) approach, which is a matrix representation of Network-of-Networks.

Due to the feasibility and versatility of using networks of networks as an approach to manage the complexity in Product Development, established practices in Networks, Design Structure Matrix (DSM) and Systems disciplines can be used in analysis of raw data.

Observation 3: A Network-of-Networks can be applied to systems that can define nodes and edges. Using the connectivity between people and tasks in organizations as nodes is a feasible and useful way to model Product Development.

III. METHODOLOGY

A. Data Collection

In order to understand a Network-of-Networks to deal with complexity, relevant data is needed. In order to know what data is needed, the objective of the analysis must be defined. Based on papers studying team efficiency and innovation [3, 4] and mechanics of networks [13], a feasibility analysis centered on Product Development network connectivity, cross-functionality and connectivity to decision-makers are deemed to be the most important factors to consider. Each of these seem to be embedded in knowledge of the individual. As such, each edge will represent the flow of information, each node has the ability to use this information to process it into knowledge and pass on further information.

In the context of an organization this could be done by collecting survey or email data. When done on a large enough scale, survey data would provide a holistic picture of the company, but there are clear issues when asking who is connected to whom and with answer biases, which might be subject to lack of self-awareness or simply to "office politics" (e.g. providing dishonest answers given an individual's organizational aspirations) . Collecting email metadata and keywords in a manner shown by Tyler et al's email spectroscopy [15] would allow for sufficient data to create a network of connectivity, networks showing what functionality/discipline each person has and is connected to (see Fig. 2) and how each person is connected to decision-makers. Additionally, email data could be collected within set time-frames and cross-referenced with project gate-ways. However, it does not account for people sharing information in other forms (i.e. face-face communication, phone calls, reports etc...). This could potentially limit the integrity of the network. As such, it is necessary to cross-reference this data with surveys and interviews to ensure that the most important connections are in fact being accounted for.

Model Attribute 1: Using email data to build the Network-of-Networks provides an unbiased, systematic and continuous source of data. However, it is important to remember that it does not provide a complete picture.

However, whilst this would yield interesting information on the organization being investigated, this would yield no context. As such, in order to provide a meaningful analysis, requirements progression would need to be tracked and measured. It is especially important to realize that requirements are not simply cumulative and are subject to volatility [16, 17]. This needs to be addressed when modelling Product Development, and needs to be validated.

Model Attribute 2: Requirements progression provides continuous and relevant measurement of Product Development progression, even accounting for volatility. This could be used to calibrate the model and is central to the analysis.

B. Building The Model

1) Building the Networks

Using email data, it is possible to create nodes using sender information, and create edges using receiver information to create a connectivity network as shown in Figure 1.

Model Attribute 3: Using sender and receiver data, a connectivity network can be created for the entire organization.

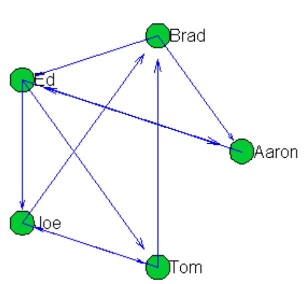

Figure 1 - Network of email connectivity

Furthermore, using keywords in emails, it is possible to determine the modularity of discipline/power based on the frequency of occurrences of certain words and how connected a particular node is to that word. This is the basis of the Network-of-Networks in this instance.

Model Attribute 4: Creating categories using keywords provides a systematic (albeit subjective) method for differentiation between node ability.

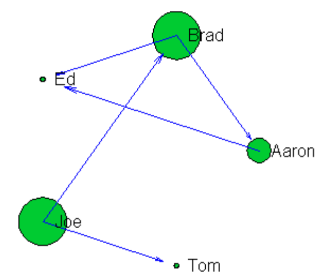

Figure 2 - Network of emails containing 'Flow' keywords

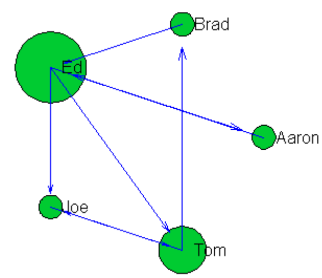

Figure 3 - Network of emails containing 'Design' keywords

The size of the nodes in Figures 2 and 3 represents the task density in specific categories. This essentially shows how biased a person is towards a given category. In order to determine how relevant a category is to a person, it is possible to apply the Google PageRank algorithm [18] that provides a score as to how relevant a particular node is. By modifying PageRank to account for multiple occurrences in neighboring nodes, this becomes an ideal method to determine bias.

$$G_i = \frac{x_i}{k_i} + (1 - d) \sum \frac{G_j x_j}{k_j} + \frac{d}{N}$$

Where G is the Google-number used as the bias, whilst i denotes the current node and j denotes node i's neighboring nodes, d is the damping factor (usually taken to be 0.85 [18]), k is the number of outgoing edges and x is the number of occurrences of keywords of a given category.

Model Attribute 4: Node bias towards given categories can be attributed by modifying Google PageRank as shown above.

For example, Figure 2 shows the connectivity of keywords pertaining to "Flow" as a discipline. Keywords here include CFD, flow, coefficient of discharge, Cd, Cq, cavitation as well as variants of these. As such, the larger the nodes are in the figure, the more tasks a particular person is assumed to have within that category. As per the modified PageRank algorithm, the number of occurrences in a given node and its neighbors are taken into consideration.

Additionally, with large enough samples, the modularity centrality as shown by Newman [19, 20] can show clear communities as is shown in Figure 4.

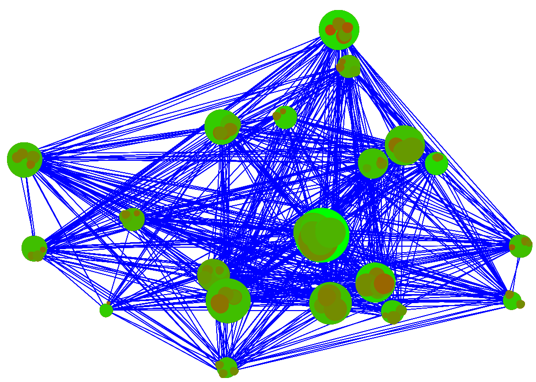

Figure 4 - Clear communities with the Network can be determined

Comparing the communities of practice within the connectivity matrix to the node bias would ideally show a close match. However, any discrepancy could show anything from cross-functionality to improper team integration and lack of leadership. Furthermore, analyzing the individual networks in the context of Network-of-Networks could give further insight into successes or failure of the Product Development when analyzed within the correct innovation framework. As such, this approach by itself is a tool to manage complexity.

Model Attribute 5: Communities of practice can be automatically defined by applying Newman's network modularity. This will allow the structure of the network to be analyzed and can be compared to the user defined categories.

2) Knowledge Transference

The network mechanics, although useful and able to deal with complexity in its own right, provides no context in relation to completing requirements. Whilst there have been several papers that have directly correlated the successful completion of a project to knowledge transactions [21], there are few studies that look at the context of what is shared or whether it is either tacit and explicit in its nature and even fewer that try to model these parameters.

Past research has concluded that the fundamental objective in Product Development is to develop explicit knowledge [22]. As such, there needs to be a direct link between the transfer of information and the completion of requirements and its inherent volatility. To that end, the network approach could be complemented by an Agent-Based Modelling approach. The driving factors of Product Development (represented by nodes' biases) could be used to define the mechanics of information sharing and knowledge development. In a Product Development system currently being investigated, there are several people who are in charge of consolidating this information into an actual design, which could be represented as gateways to the design-space.

The strength of this approach is that it creates a new model that could be calibrated to match real data. Whilst many knowledge diffusion modelling attempts lack empirical evidence [23], this method uses empirical evidence to provide a deeper insight of the nature of design as a complex dynamic process.

Model Attribute 6: Knowledge development and information sharing are modeled to directly represent the development of a product. This will illuminate the core dynamics of the Network-of-Networks and allow a microscopic view of the system.

IV. ANALYSIS

The method described in this paper provides a suitable network model to manage the complexity within Product Development. It defines a network of connectivity within an organization, attributes user-defined categories such as employee functions to each node, cross-references these to modular communities of practice and finally has the ability to provide user-defined rules of information sharing and knowledge development to create a dynamic network. This section will highlight several important relationships that could occur.

A. Analysing Communities of Practice

Cross-referencing the modular (natural) communities of practice to the defined categories that are deemed important will provide a lot of information as to what the efficiencies or deficiencies an organization might have.

In Product Development, when comparing employee functions, a natural community would be expected in a given project. If there is a discrepancy, and the functions are in fact spread out through the natural communities, it could be an indication of three things.

- The communities could be highly cross-functional.

  This implies that this function is performing very efficiently. This should be characterized with high connectivity to the node's community as well as connectivity to Project Management (either through a Project Management function or to leadership) and to other practitioners of this function either directly or through strong links (determined by the strength and degree number of the shortest path) [19].

- There is very little integration on that particular function.

  This implies that this function is performing inefficiently and ad hoc. This would be characterized with the only strong connection being to other members of the community and only weak connections to Project Management and to other practitioners.

- The function is not deemed important enough to warrant a dedicated employee base.

  This explains the nature of the function with respect to the Product Development process and implies that the function is not important in the current organization. This could be characterized with weak connectivity overall.

If the natural communities match the defined functions, it is a strong indication of function-driven teams. If this is in discrepancy with the organization's team definition, then it would indicate that teams have not bonded yet and that the company is in a transition period. Otherwise, there are three main situations that could arise.

- There is strong connectivity between all communities.

  This represents the ideal situation and strong communication both vertically and horizontally within the organization.

- There is preferential connectivity between the communities.

  This is most likely the most realistic case and could imply several different things. It could imply a strong connection between two functions if there are many direct links between two communities, highly connected nodes in certain communities that improves the community's connectivity strength or strong integration between specific communities if there are a few strong links between two communities [13].

- There are weakly linked or isolated communities.

  This implies that there is little or no connection between communities. This could be down to the network that is being studied not being large enough, but it is more likely that there is a serious lack of integration, which decreases the understanding of each others' requirements. Furthermore, any link that might exist between such communities are even more susceptible to attacks to the network (for instance, a person connecting the two communities leaves the organization) [19].

It is equally important to consider how robust a network is [13]. Any targeted disruption to a scale-free network could have catastrophic effects. This is true for the entire network as well the integration of specific communities.

B. Knowledge Transference

The knowledge transference model will provide an analysis on two levels. Firstly, it will provide a direct view of any enablers and bottlenecks of the information flow and development. It does this through a dynamic view of the system across time-steps. Understanding how these affect the gateway nodes to complete the requirements will give significant insight into where the system will need interaction to hasten the Product Development process. Therein lies the second level of the analysis, by interacting with the process to improve it, the nature of the System will change and it might have a complex change on the overall response. Using traffic as an analogy, a change in the traffic could cause a plethora of improvements and deteriorations elsewhere.

In fact, this alteration and monitoring of the subsequent effects is one of the few deterministic ways to model the effects of making small changes to a network. Based on this, it is then possible to suggest what the network should look like, thus creating a tool to systematically analyze the risk and to optimize the organizational network of an organization.

Model Attribute 7: A pragmatic framework analysis has been provided in Section IV that can be used with the model.

V. CONCLUSION

A tool to manage the complexity of Product Development has been created based on a Network-of-Networks approach. This tool gives insight into the dependencies of any decision-maker in the organization. A set of accompanying analysis lenses have been given for high-level insight on a pragmatic level. In addition to this, an Agent-Based knowledge propagation model has been embedded to the tool that provides a calibrated requirements progression. By analyzing the information flow between nodes and the knowledge development within nodes, it is then possible to predict, explain, illuminate the core dynamics, guide data collection for further investigation to reduce the risk of management choices and provide suggestions for optimization. Furthermore, this approach provides a micro-perspective of the network due to the sensitivity the embedded network dynamics.

As such, this tool could be used by decision-makers in a number of positions. It highlights everyone's influence on the Product Development process. It defines whether a node is an enabler or a bottleneck in the information sharing process. It explains the macroscopic nature of teams, which can be compared to the overall nature of innovation in the organization and analyzed whether it is enabling or is maladjusted for the overall strategy. On-going research is collecting data as is outlined in this paper to review and validate the findings and further develop the analytic framework.

VI. ACKNOWLEDGEMENTS

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