Globalization, the New Economy and Project Management: a Graph Theory Perspective

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ABSTRACT

The satisfaction of human needs requires resources, tangible ones, metals, machineries … and less tangible ones like human time and human capital. Specialization creates a distance between resources and needs. Industrialization and its successor, globalization, have kept increasing this distance, along its geographical dimension, but also along its organizational dimension. Specialization poses numerous challenges: information collection, coordination, communication, motivation, enforcement … Since the early industrialization transformation of the artisan shop, firms are the main response to these challenges. Firms have devoted an increasing amount of human resources to management tasks over the last century. An avenue to account for the growing popularity of PM among firms under globalization is to show how PM approach can be, in some context, a more economical way to organize management tasks than traditional business management. The paper presents, first, the hypothesis from a historical perspective, using a concept of distance from theory of value and transaction cost analysis. This translates management tasks into costs but lacks preciseness. From another perspective, a structured set of management tasks is a graph connecting a pool of resources in some location(s) with things fulfilling needs elsewhere. The hypothesis becomes one about the properties of the graphs, such as the relative duration of the critical path, of the PM and other approaches to meeting some of the challenges, for instance coordination, raised by specialization. The paper then explores ways to bring preciseness with graph theory applications to management at operational and organizational levels, emphasizing PM.

keywords: Project Management; New Economy; Cost Analysis; Critical Path; Theory of the Firm

1. Introduction

The rising popularity of Project Management (PM) in the globalized new economy raises questions about ways of managing and organizing things. The focus, in the study of production costs, was for a long time, on decisions related to standard costs of transformation processes (materials, energy, human time and effort along the process). As recalled by Milgrom and Roberts (1992), the transaction (the transfer of goods or services from one individual to another) has become "the most fundamental unit of analysis in economic organization theory" (p.21). They point out "individuals create and manage an organization, are indivisible decision-makers who actually decide, vote or act … their actions determine the performance of organizations in serving people's intended purposes" (p. 21). This has contributed to identifying another category of production costs, organizational ones, frequently qualified as transaction costs and broken down into coordination costs and agency (or motivation) costs. It has also shed light on differences in the organizational structure of production and on variations in firms' boundaries like the strong tendency to vertical disintegration in many sectors and the opposite trend in a few others.

Although the human mind has always been at the forefront of technology developments and productivity gains, its importance as revealed for instance by the human capital component in total value creation, has been rapidly growing in the new economy. This evolution raises managerial and organizational issues that transaction analysis can help to address. Transaction analysis can also contribute to the understanding of the continuity from the first industrial revolution to current globalization. A generalized notion of distance derived from the theory of value becomes useful.

In order to fulfill human needs, resources are moved, combined, and transformed into goods or services readily available; in other words, means are turned into deliverables.

Between resources and needs, there is a distance in time, in the geographical space and in the many-dimensional space of physical transformations (coal and iron ore turned into steel, steel and petroleum turned into appliances …). Contrary to first impressions created by major innovations in information and communication technology, everything in the globalized new economy tends to be further apart, globalization is associated with some kind of organizational space whose dimensions are growing, as is its geographical space. Along with this century-old tendency, the management of things requires more and more resources.

The proposed communication is in three parts. The first part (section 2) gathers facts on specialization and exchange, on the origin of firms, on the emergence of standard business management, and on the origin of PM. It then formulates a hypothesis on the popularity of PM, conjecturing PM is a more economical way to organize management tasks. The transaction cost analysis used in the conjecture lacks preciseness. The second and third parts of the paper use graph theory to go beyond this limitation. Lines of communications, the capacity of systems, network communication structures are some of the themes addressed. Although inspired by the work of Hurwicz on informational decentralization, of Radner on hierarchy and information processing, of Reiter on coordination and the structure of firms, and of Mount and Reiter on complexity in economic behavior and organization, the work is exploratory. Hopefully it will pave the way to developing graphs to represent different ways of organizing management tasks such that the properties of the PM graph, for example the duration of the critical path could be shown to be more economical / shorter in some circumstances than the properties of graphs of other management approaches.

In the paper, PM is opposed to standard business management (SBM), which combines fields of applications or functional areas of business like marketing, human resources, leadership, strategy, corporate finance, financial accounting, …. This does not reject the existence of some common denominator. For instance planning, very closely associated with PM in the analysis, is a topic covered in standard textbooks on management or business management (Robbins et al (2006), Althouse et al (2014) …). This opposition is used for analytical purposes to emphasize what may characterize more specifically PM; it is academic. In practice, PM and SBM will be complementary within a firm. Also for analytical purposes, the description and structuring of management tasks provide a partial definition of a firm or an organization. The section "Firms beyond analogies", in Papillon (2018), proposes a complete definition of the firm.

Some countries over recent decades have privatized activities usually carried on by public administration, particularly the construction of infrastructures. The organization of the "production" of infrastructures usually followed, explicitly or implicitly, PM principles. Firms taking over this production did not re-invent the wheel. The growing popularity of PM in firms analyzed in the paper goes beyond this privatization factor.

2. Managing in the New Globalized Economy, PM and Transaction Costs: a First Hypothesis

2.1 Productivity, Exchange and Firms

In a general sense, production refers to any human activity aimed at fulfilling human needs. Consumers cooking raw vegetables bought at the grocery store perform a producing activity similar to the one of a restaurant chef. The economic analysis classifies economic activities in three categories: production, exchange, and consumption (Hurwicz and Reiter (2006)) and in this classification, production has, however, a less general sense. It refers to production for others, excluding households' efforts to produce goods or services (meals, health care, child education, house renovation, auto mechanics, snow removal around the house …) fulfilling directly their needs.[1]

Artisans are mostly gone. For instance, shoemakers producing a custom-made pair of shoes from pieces of leather have almost completely vanished. Somewhere in the 19th century, between the first and the second industrial revolution, manufacturing firms of shoes took them over. Task specialization in these firms increased the productivity of human effort, reducing production costs and prices, making shoes more accessible. In agriculture, and much earlier in time, innovations like the use of manure as fertilizer and crop rotation increased productivity, motivating a gradual switch from self-sufficient farming to specialized production, which implies producing for others. Putting aside the case of centrally planned economies like Russia and some other countries in the 20th century and putting aside public services supplied at no charge for users, producing for others is synonymous with producing for exchange between economic agents in the role of buyers and sellers. Using common parlance, in the private sector, the exchange is a corollary of specialization.

In the early days of industrialization, firms in most economic sectors were small and served a local clientele, they then increased in size and their clientele extended geographically, to regions and beyond, up to the contemporary global economy. Business cases gathered by Besanko et al (2010) in their chapter "The Power of Principles: A Historical Perspective" compare the doing of business in 1840, 1910 and today, capturing the essence of this evolution. Innovations in agriculture, manufacturing, and communication, along with the steam engine, applied to marine transportation and to land transportation with railroads, were early determinants of this evolution. By reducing the cost of distance, they kept increasing the net gains of doing transactions with people and firms, either as customers or as suppliers, further away, inducing more specialization.

[1] These activities are analysed in household economics, but unless otherwise indicated, are not part of production.

Although transportation and communication costs are usually qualified as "natural" barriers to trade, benefits from transportation and communication innovations that have reduced these barriers are conditional, to some extent, upon the availability of public funds for infrastructures (canals, harbors, railway tracks, bridges, …). Tariff and non-tariff barriers are another policy contingency in the long-term evolution from early industrialization to globalization; like natural barriers to trade, they have a restrictive effect on specialization and exchange. In a simple transaction model, natural and policy barriers to exchange composed, with transaction costs, the cost of exchange activity (CEA) (Papillon (2018)).

The firm is the response to the organizational challenges posed by specialization (Demsetz, (1995)). The firm takes numerous forms designed by a variety of expressions, each one referring to a number of legal, contractual and cultural attributes: individual businesses, small and medium-sized businesses, partnerships, private corporations, public corporations, conglomerates …. Some of them will be one site or single plant operations, and others dispersed geographically. Their common denominator is specialized production for exchange.[2]

Coordination, motivation, and the discovery or determination of terms of exchange and transaction prices (for products and inputs including human time) are the three challenges firms, as organizations, will meet. Their "raison première" is to reduce the cost of exchange activity. At this level of analysis, profits or returns on investment are not objectives but a constraint imposed on managers. This constraint addresses motivation problems (Papillon

[2] A cooperative gathers people producing for their own needs and is not a firm although there can be specialization. Some producing organizations, designed as cooperatives because of equal ownership share among a fixed number of people, share however the above common denominator with firms and are firms in the current context.

(2018)) associated with specialization and some ownership structures, particularly widely dispersed ones, as pointed out a long time ago by Berle and Means (1932). Motivation problems, however, go beyond ownership consideration. The production of a firm being a team outcome, sorting out individual contributions is not wholly feasible. Furthermore, with respect to management tasks in general and with respect to firms of the new economy in particular, human effort is largely intellectual, rather than physical, and therefore non-observable.

2.2 Coordination, Management and Specialization

Specialization requires coordination from firms outside (with suppliers, clientele …) and inside as the efforts of many people are combined. As recalled by Besanko et al (2010), whenever “the best action for one person to take” depends “on the actions taken by others or on the information held by others” (p.78), it is important to find ways to coordinate. As an organizational solution, each firm is located along a continuum going from a highly centralized structure with decision-making authority concentrated in a few persons to a highly decentralized structure with authority dispersed among many people. With more centralization, directives requiring information transfers to and from the authority center play a greater coordination role and mutual adjustments among people a lesser one. The coordination mechanism of a given firm combined in some specific proportions a “directives” component, relying on management, and a “mutual adjustment” one.

A larger team of people allows more specialization while requiring more coordination. With a growth in the size of firms, one should observe a growing share of resources devoted to managerial tasks. The evolution of firms and the evolution of employment composition in the 20th century confirm this conjecture. In a survey paper on the economics of managing, Radner (1992) reports figures showing a close relationship between the growing share of large firms in total employment and the growing share, in total employment, of occupations in managerial categories. While clerical jobs represented barely a few percentage points of total U.S. labor force at the turn of the century, they represented nearly 20% in 1970 and managerial related occupations as a whole moved above the 40% mark in 1980. A classic reference on management and organizations is *The Structuring of Organizations* by Mintzberg (1979) where it is also argued "The larger the organization, the more elaborate its structure … the more developed its administrative component" (p.230), and Mintzberg adds, citing many authors, that "the evidence for this hypothesis is overwhelming".

In another historical study, similar to Radner's research, Wallis and North (1986) estimate the evolution of the share of GDP captured by economic activities for the making of exchange; what they call the transaction sector. "The growth of the transaction sector is a structural change of the first order" (p.125), the share going from around 25% of U.S.A. GDP in 1870 to 50% in 1970.[3] The phenomena respectively studied by Radner and by Wallis & North are not identical sets but are largely intersecting ones. Their respective growths over time come with specialization. In *The theory of value*, Debreu (1959) introduces a multi-dimensional space for the complete description of each product (physical characteristics with location and date); this space embodies a generalized notion of distance between resources and needs. Transportation, communication, management, and finance, which are activities required to cover this distance, do not have value in themselves and their reduction can be a source of value creation. In one of his early writings, Hurwicz (1972) emphasizes this point by distinguishing allocatively used resources – those required by the distance referred to above, from substantively used resources – those going directly to the satisfaction of a need. Implicitly, transaction cost theory makes a similar distinction.

[3] In Wallis and North research, "transaction costs include the value of the labor, land, capital, and entrepreneurial skill used in making exchanges" (p.97).

Managing consists of "figuring out what to do in contrast to doing it" (Radner (1992), p. 1387, citing Frank Knight (1921), *Risk, uncertainty, and profits*). Management tasks include: to observe the environment and results of past actions, to process and communicate information, to make decisions, to monitor the actions of other people, to hire and to fire, to train and to teach, to plan, to solve problems, and to exhort, to persuade (other employees, lenders, investors, …), to set goals and values (Radner (1992), p.1388, 1389). Resources allocated to the "doing" have some direct value since the product produced will eventually fulfill a need. This is not the case of resources allocated to management tasks. Given their growing share of all resources used by firms, there has been and there is an implicit and sometimes an explicit search for economizing on resources consumed in managerial tasks. In the current context, the growing popularity of PM is an indication of this search. It is one indication among others.

From the late sixties to the present, the strong tendency for contracting out by large firms is one more fact on the trend towards more specialization among firms. In the auto industry, for instance, widely known makers of cars are increasingly specialized in the conception of new models. When it comes to the making of cars, and because they are less and less vertically integrated, their role is more and more limited to the assembling of parts bought from numerous suppliers. In the terminology of input-output models, it consists of replacing primary inputs, labor, and capital, engaged in the making of motors, brakes or suspension components, by intermediate inputs - these same parts being intermediate inputs produced by other firms. Contracting out with suppliers requires coordination and it is a managerial task. Even if contracting out reduces eventually the average size of firms, the trend since the early 20th century, reported above by Radner and by Mintzberg, for a growing amount of resources going to management tasks is unlikely to be reverted. It is not firm size by itself, which has triggered management requirements but specialization, and contracting out brings more specialization. Globalization facilitates specialization without requiring firms of larger sizes.

Frequently, the theory of the firm will picture it as a network of contracts: contracts with primary or intermediate inputs on the cost side and contracts, on the revenue side, with consumers or other firms buying the firm's products. Among the characterizations of these contracts, completeness has received a lot of attention. Contracts about products, either goods or services, bought or sold by the firm will tend to be as exhaustive as possible, describing in some detail the service or the product and describing, if the transaction covers some time period, how future events will be handled by the parties to the transaction. Contracts about primary inputs will be shorter. For labor employed, the description of tasks won't go much beyond occupation classification, decision-making authority of managers being some kind of "cure for the lack of completeness".

Sometimes, business strategists will argue that contracting out saves on production costs and producing internally saves on transaction costs. A supplier wholly devoted to the production of an intermediate input bought by many firms will be more productive since more specialized than any of them. Implicitly, this interpretation of transaction costs emphasizes the coordination challenge met by firms and overlooks the other two aspects of their "raison première", motivation and determinants of terms of exchange, including those among various categories of employees. With respect to coordination problems, management is a significant part of the solution. For matters related to the other two aspects, management is not only on the solution side; it is also a part of the problem being addressed.

2.3 Characterization of PM: A Transaction Cost Hypothesis and Beyond

PM as a well-codified field of management is only a few decades old. In this view of PM, Sato (2016) recalls the importance of major projects like Apollo in the 1960s and subsequent developments, which imported teamwork, cooperation, risk management, adaptation and strategy into PM. From the perspective of management in general and the theory of the firm in particular, the early days of PM go much further back in history.

As already pointed out by a number of authors, it may go very far back, to when human social life reached a stage of development allowing endeavors of some magnitude in the domain of construction. One can imagine that a building or other structure, frequently for defensive purposes, was envisioned by the power center (religious leader, military chief, …) and resources (materials, slaves…) were made available to some "manager" conditional on some projection regarding how and when the "thing" would be done. Although simple, this historical account helps illustrate the basic concern of project management on being as explicit as possible on the "thing" to achieve and its focus on planning, particularly the identification and scheduling of tasks in order to get the thing done when expected. Right from the beginning, the motivation of the manager appears to have been a matter of concern. At the risk of being simplistic, the realization of a project translates into a projection of scheduled tasks. The description of the thing to achieve, the when and the how as a whole, as introduced here, is the Iron Triangle or Triple Constraint in a comparative management history context. Historical circumstances surrounding the development of production and firms' management are different from PM. In the production of military equipment, or in the mining sector, or along with the transformation of artisan shops into manufacturers, the existing ways of doing provided a comparable in the search for better ways to organize production, for reducing costs and/or improving the quality of goods produced. In other words, existing ways of doing have allowed for conjectures on the effect of new managers and managerial practices on sale revenues and costs, that are on value creation. Trial and error with comparables in the background have guided the development of business management and its integration of knowledge from disciplines like mathematics, psychology, and economics, which is SBM. The lack of comparables characterizes the context in which PM has developed through the ages. Because of various factors, among others the geography and location of the site and of the resources required, each project has no comparable for many of its dimensions. Through projection and prospection over numerous possible contingencies, PM constructs some kind of ideal scenario acting as a comparable, in guiding and binding management tasks. Furthermore, and very essential, a comparable gives some control over managers, helping to reduce the costs of meeting the motivation challenge with this group.

In Papillon (2017, 2016), there is a hypothesis to account for the growing popularity of PM. The advanced thesis is that PM, for firms of the new economy, is more conducive to value creation than SBM, the argument being that human efforts in these firms are primarily creative and have little comparable for guidance or evaluation, as the historical circumstances of PM emergence. As a theoretical framework to formulate and validate the hypothesis, transaction cost theory with its focus on coordination and motivation is an obvious candidate. Accordingly, PM would be more efficient or economical because it saves on transaction costs.

In a literature survey on transaction costs, however, Allen (1998) observes that conceptual views on their nature are not consensual and there can be large variations in their measure, which is sensitive to the way of separating transaction costs from production costs. More fundamentally, “production and transaction costs generally depend both on the organization and on the technology, which makes the conceptual separation between production and transaction costs troublesome” (Milgrom and Roberts (1992), p.34). Furthermore, as discussed above, when it comes to motivation, putting the costs of managerial tasks in transaction costs runs into circularity since management is not wholly on the solution side but is part of the problem to address. In other words, transaction cost analysis lacks preciseness to count how much more economical PM can be in some context.

Graph theory has been very useful to address a number of practical problems faced by management in general as well as PM in particular. Means are transformed into deliverables, or in economic terms, resources find their way to human needs, under management guidance. On the way to cover the distance between resources and needs, there can be many paths. From this perspective, a structured set of management tasks could be represented by a graph connecting a pool of resources in some location(s) with things fulfilling needs elsewhere. The hypothesis about PM being, in some context, more economical than other management methods is analogous to the search of the shortest path in graph theory. The hypothesis becomes one about the duration of the critical path of a PM graph being smaller than the duration of the critical path of an SBM graph, duration referring here to time and other cost dimensions of managerial tasks.

3. Graph Theory, Management and PM: An Operational Perspective

Many management and PM problems are solved using tools based on graph theory techniques. The link with graph theory is not always evident. This is not surprising considering that large problems are solved using software packages where algorithms based on graph theory work in the background. A discussion of selected management problems solved using graph theory-based algorithms will show this link. Problem selection is motivated by the research hypothesis; the scope of graph theory applications to management is broader.

The maps in airplane magazines that show the routes the airline offers between cities are good examples of graphs. The cities serviced are usually drawn as circles and the routes are usually drawn as smooth curves connecting the cities. A curve between cities A and B shows that there is at least one non-stop flight between A and B. If there is no curve between cities C and D then at least one connecting flight is needed in order to fly between C and D. Definition: A graph G is a pair (V,E) where V is a non-empty set, the vertices (u,v,w,...), and E is a set of pairs of vertices of V, the edges (uv,vw,…). In the airplane magazine map example, the cities are the vertices and the edges are the curves. [4]

Highway systems can also be represented by graphs. The vertices are the towns (A,B,C, ...) and two towns are joined by an edge if they are linked by a highway. In order to compute the shortest driving distance between any two towns in the graph additional information is needed – the highway mileage between two towns joined by an edge. Adding this information m_{uv} to each edge uv gives a weighted graph.

Driving in large cities often involves one-way streets. You may have to drive around the block to get to your destination, e.g. driving from u to v is longer than driving from v to u. To reflect one-way restrictions the edges can be changed to ordered pairs (i.e. uv is different from vu); the edge uv is drawn as an arrow from u to v. This is a directed graph.

In PM, the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) both use weighted, directed graphs. A directed graph, or digraph, G is a pair (V,E) where V is a non-empty set of vertices (u,v,w,...), and E is a set of ordered pairs of vertices of V, the edges ((uv),(vu),(uw),…). A weighted graph/digraph is a graph/digraph G=(V,E) where each edge uv has a real number w_{uv} associated with it.

A graph with vertices $v_1,v_2,\dots v_n$ can also be represented by an n×n matrix. If there is an edge from v_i to v_j then the entry in the i^{th} row and j^{th} column of the matrix is 1, otherwise the entry is 0. For a weighted graph or digraph the entry in the i^{th} row and j^{th} column of the matrix is w_{ij} if v_iv_j is an edge; otherwise it is 0.

3.1 Shortest Paths

[4] In graph theory the vocabulary varies; vertices are also known as nodes, edges are also known as arcs, and graphs are also known as networks. Sometimes networks have additional conditions associated with them.

Managers are often faced with finding the most economical way for their staff or stakeholders to travel to a particular location. When the travel cost is the automobile allowance rate per kilometer, the lowest cost trip will be the shortest. Given a travel map or graph with the distances between cities, the lowest-cost trip can be found, however, more than one route may have the same lowest cost.

When an emergency vehicle is deployed to a location in the city the goal is to arrive as quickly as possible. Sometimes this will be the shortest route, but sometimes a longer route will be faster. In this case, a travel map or graph showing the time to travel between any two intersections will be needed to find a solution.[5]

In graph theory, a "route" is called a path and a path that begins and ends at the same vertex is called a cycle[6]. When the edge weights in a graph or digraph are non-negative distances the shortest path between any pair of vertices in a graph can be computed. If the weights represent other non-negative quantities, such as cost or time, the "shortest" path, e.g. the lowest cost or the quickest, can be computed using the same techniques. However, if weights can be negative and a cycle with negative length exists then computation problems may occur.

In many applications, it makes sense for edge weights to be negative, for example when the weights are income (positive) and expenses (negative). Think of a currency exchange graph where the vertices are the currencies $c_1,c_2,\ldots,c_n$ and the edge weights are the cost of exchanging c_i for c_j. If there is a cycle in the graph where the net cost of exchanging currencies is actually negative one can make money by exchanging currency until currency rates are changed by some arbitrage.

[5] In this section, unless stated otherwise, it is assumed that graphs are connected, i.e. there is at least one path between every pair of vertices.

[6] In general a path p or cycle c from v_1 to v_k can be described by listing the vertices in the order they are traversed, e.g. $v_1, v_2, v_3, \ldots, v_k$.

Dijkstra's algorithm can be used to find the shortest paths when the edge weights are non-negative. For digraphs with negative edge weights the Floyd-Warshall algorithm will either find the shortest path or detect a negative cycle and stop the computation.[7]

In some situations, finding the shortest path in a graph may not correspond to an optimal solution. For example, if the weights on the edges of the highway graph are changed to the average speed of driving between the cities then the shortest path can be found, but its length is not the average speed of the trip, the total distance covered and the total time taken must also be taken into account. If the weights are changed to total fuel consumed on the highway between the cities then the shortest path would be the route that used the least fuel. When creating graphs to model a situation it is important to check that it makes sense to add the weights of the edges before beginning to compute the shortest path, in other words, that the shortest path measures something meaningful.

3.2 Critical Paths

Project managers need to keep track of the progress of projects and ensure they stay on budget and on time and take action when the project is not going as planned. Graphical representations of the project can be used to coordinate activities or tasks and to compute the number of resources required. Two examples are CPM and PERT.

In a CPM weighted digraph, the vertices are the activities that need to be carried out to finish the project. An edge is added from u to v if v cannot be started until u is completed. CPM puts the duration of the activity in the vertex, but for this discussion, assume the weight of edge uv is the duration to complete activity u. The length of a path is the sum of the durations on the path and the critical path is the path from the beginning of the project

[7] For more information about Dijkstra's algorithm and the Floyd-Warshall algorithm see Chapter 8 in Balakrishnan (1991).

to the completion of the project having the longest duration. This longest duration is the duration of the project[8]. If any activity on this path is delayed the whole project will be delayed. Delays in completing activities not on a critical path will not delay the final completion of the project up to a point. To shorten the project duration additional resources will have to be invested in the project to speed up one or more of the activities on the critical path. Speeding up an activity on the critical path by 3 units does not guarantee the whole project will be completed 3 units sooner because of the interdependence of the other activities – the critical path needs to be recomputed. CPM algorithms[9] can be rerun to incorporate information about delays, effects of remedial actions and changes in future timelines to see the overall impact on the project.

Similarly, PERT looks at lengths of paths in a weighted digraph where the vertices are the milestones of the project. Again, the duration of activities can be added as edge weights, the longest path is the duration of the project and the algorithm can be rerun to incorporate changes during the planning process and as the project progresses.

3.3 Capacity of Systems

Designers and managers of systems that transport commodities such as information, traffic, oil, and electricity need to know if the system can meet the peak demands of the community. Such systems are often represented by directed graphs where the vertices are the mechanisms that “push" the commodity (e.g. servers, intersections, pump or generating stations) and the edges are the transmission or transportation links (e.g. cables, roads, pipelines, transmission wires). The maximum volume of a commodity that can be

[8] The project will have one duration, but there can be several critical paths, all of the same length or duration. To speed up the project **all** the critical paths have to be shortened.

[9] To compute a longest path in a weighted digraph one can multiply all the edge weights by -1 and apply a shortest path algorithm.

transported via a link is the edge weight of the link, so edge weights must be positive[10]. For ease of discussion, assume there is one source vertex s and one terminal vertex t in the system, and the other vertices are intermediary points[11].

For a commodity to move through the system in a steady-state, the volume flowing through each link must not exceed the capacity of the link. The volume flowing into s must be zero and the volume flowing out of t must be zero, and the volume flowing into any vertex other than s and t must equal the volume flowing out of that vertex (i.e. the commodity cannot "disappear" and no pooling or back up can occur). An assignment of the volume of commodity to each edge such that all these conditions are satisfied is a **flow**, and the value of the flow is the total commodity flowing out of s (or into t). Algorithms exist to find the maximum flow. Note that when the system is operating at maximum flow the volume in some of the links may be below capacity and may even be zero.

Many graph problems can be solved by transforming them into another form with an existing solution or algorithm and then applying that solution or algorithm. For example, suppose an organization with a Project Management Office (PMO) wants to maximize the number of projects that can be accepted in the coming quarter without hiring any new project managers. This can be transformed into a flow problem as follows. Construct a graph with two sets of vertices, the project managers $m_1,m_2,\ldots,m_n$ and the projects $p_1,p_2,\ldots,p_r$. If project manager m_i has the skill sets needed for project p_j add an edge from m_i to p_j with weight 1. The source vertex will have an outgoing edge to each project manager with weight 1. The terminal vertex will have an incoming edge from each project

[10] Negative flows can occur in electrical networks where customers are allowed to feed electricity they generate by wind or solar power back into the grid.
[11] If this is not the case add a new supersource vertex and connect it to each source vertex with infinite (or very large) capacity; and add a new superterminal vertex and connect each terminal vertex to the superterminal vertex with infinite (or very large) capacity.

with weight 1. The maximum flow of this system will be the maximum number of projects the project managers have the skill sets to carry out on a full-time basis[12].

3.4 Lines of Communication

When firms create their emergency communication plans they may incorporate some redundancy to ensure communications can continue even in the event of an outage or other communication disruption. One way to detect communication redundancy is by counting the number of edge-distinct paths (paths that do not share any edges) between two vertices in the communications graph. For example, if there are five edge-distinct paths from u to v then the organization can sustain damage to four edges (perhaps one on each distinct path, or several on one of the paths) and still maintain communications. The number of edge-distinct paths between two vertices can be found by transforming the communication graph into a flow problem with each edge-weighted 1. Then the maximum flow is the number of edge-distinct paths[13].

3.5 Software Considerations

After an organization acquires software to solve graph problems discussed in this section, what factors should be considered about rerunning the software to deal with changes?

One consideration is whether the cost of maintaining, reviewing and updating the information about the project and rerunning the software is in line with the expected benefits of the revised solution. For PM software it is expected that the information will be updated throughout the project and used to create reports so information collection is built into the project and the ability to update information easily is a standard software requirement. For other management problems, this may not be the case. Factors to consider include: a) the likelihood or frequency of the information changing, b) the cost of acquiring

[12] For more information about maximum flows and transforming scheduling problems into flow problems see Section 13.3 in Roberts (1984)

[13] For a formal proof, see Menger's Theorem, for instance in Bondy and Murty (1978) p. 203

or updating the information, c) the time and cost to input the revised information. Another consideration is whether the change to the information will lead to a detectable change in the solution to the problem, and if so whether the benefit of this changed solution will be more than the cost of all these other factors.

In order to make the software run efficiently, assumptions can be made about the graphs that will be input. Another consideration before rerunning the software is whether a change to the graph that represents the problem is compatible with the design of the software. Many small changes have the potential to cause large problems:

- If a buyer for a waste product comes forward then the cost of disposal becomes negative. Does the software check for negative cycles?
- The closure of a bridge could mean delivery trucks need to be re-routed. Does the software allow edges to be removed or given a very large edge weight? Will the software raise an alert when delivery cannot be made in time or at all?
- The opening of a bridge or highway may create a new link between two cities. Does the software allow new edges to be introduced? If the edge already exists will the software raise an alert? add a second edge?

If the software packages do not raise alerts in these situations then the output the manager receives may not be the correct solution.

4. Graph Theory and PM: An Organizational Perspective

How to make sense of the growing popularity of PM in firms? There has been, for a while now, cross-pollination between PM, originating in a branch of engineering, and management principles largely inherited from humanities, social sciences, and practitioners. Above and beyond this, is there something specific to PM to explain its growing popularity?

Given the pervasive competition for income and resources, the PM approach for organizing management tasks must be somehow economical for the categories of firms and sectors using this approach more. Through a broad set of management tasks, resources are transformed into goods and services, eventually fulfilling human needs, generating income to cover more than the costs, so that there is value creation.

Despite whichever way the PM approach is economical, graph theory can show that the proportion of managerial resources will increase as the size of the firm increases, as suggested by Radner (1992) and Mintzberg (1979). Consider the graph that represents the organization chart of a firm that limits the number of direct reports to at most d and divide the vertices into two groups: those with 1 to d direct reports (managerial vertices), and those with 0 direct reports (worker vertices). As long as there are managerial vertices with fewer than d direct reports we can add a worker vertex without having to increase the number of managerial vertices. When there are m managerial vertices and they all have exactly d reports the total number of vertices is md+1, the proportion of managerial positions is m/(md+1) and a firm of size md+1 cannot have fewer managerial vertices. If we add d more vertices the number of managerial vertices will have to increase by at least 1 and the new proportion is at least (m+1)/((m+1)d+1) which is greater than m/(md+1). Graph theory can also help to gain a better understanding of other organizational issues related to management tasks, suggesting some reasons for the growing popularity of PM. For illustrative purposes, some issues related to risk management, unpredicted changes, and network communication structures are discussed.

4.1 Risk Management and Coordination under Globalization

In this section, we argue global organizations can benefit more from PM because in a global economy the greater distance between resources and needs increases the risk management and coordination needed to operate successfully.

The global economy has increased the distance of many variables for global organizations. With this increased distance comes the greater potential for economies of scale. Successful global organizations have the resources to invest in large-scale projects to achieve these economies of scale and these projects require extensive PM services. We look beyond this to how the risk management and coordination services that project managers provide can benefit the organization outside of a project setting.

As organizations go global their exposure to risk increases in part because of the wider range of certain variables experience. For example, a global organization with locations in many different geographic zones has to be able to deal with multiple natural phenomena. A location in Ottawa can expect to be affected by blizzards on a regular basis but not earthquakes. A location in San Francisco can expect to be affected by earthquakes on a regular basis but not blizzards. The risk of either location having to deal with a blizzard during an earthquake is probably negligible, but as the number of different locations grows so does the chances of the organization being affected by two phenomena close in time but at different locations.[14] Project managers deal with risk management on a regular basis and have the specialized skills needed in global organizations.

An organization considers many variables that affect performance, such as costs and projected income when making decisions. With globalization the range of values these variables can take on grows. For example, if the minimum wage ranges between $11 and $15 in Canada, adding a second site in Canada would change the minimum wage by at most $4. This may not be a major factor in choosing a location within Canada, but it may become a major factor for a global organization since countries that do not have a minimum

[14] When cause-and-effect aspects exist between the risks, such as earthquakes and tsunamis, additional analysis is needed to determine whether the combined risks increase or decrease.

wage increase the range to at least $15. As the range of a variable widens it may interact with other variables in a new way or to a greater extent than before.[15]

PM planning and coordination activities identify variables that will influence the outcome of a project and their interactions with other project variables; these techniques can be applied outside of a project framework. Oehmen et al (2015) discuss cognitive limitations and note "we are faced with a fundamental challenge of finding the "right" way of compressing complexity without sacrificing key aspects that are relevant for decision making." Managing the list of variables under consideration is a necessary exercise and it could be said the importance grows for the global economy.

Risk management is an activity that is carried out throughout the project. Contacts and communications links are established between the project manager and the units that are consulted to identify, analyze and develop mitigation strategies. If a risk should materialize, using these contacts and links will minimize the time to begin the mitigation strategy, which may, in turn, prevent the growth of any negative impacts. In addition, the PM approach helps to reduce the set of unpredicted changes for a project to a minimum during the planning phase. If an **unpredicted** change occurs within the project setting the project manager may be able to use the risk management contacts to begin determining a solution, depending on the scope of the unpredicted change. In the event of an unpredicted change outside a project setting there is another unit that may be helpful - the Planning Office (PO). The PO assesses risk for the organization on an annual basis as part of the annual planning exercise. The contacts made during this planning exercise may help an organization deal with an unpredicted change, however, these contacts could be out of date while the PM contacts may be stronger and more current. It would be interesting to study

[15] For example, if a global organization looking for a new office building site in Canada does not already have locations in areas that experience cold and snow it will have to increase the construction costs estimates for the roof so it can bear the weight of snow and for insulation to keep the building warm in the winter. It will also have to understand the relationship between type of insulation and heat loss reduction so it can increase the maintenance costs (heating) appropriately.

organizations with both a PO and a PMO to see if the two offices are in regular contact with each other and if any synergies or transfers of knowledge take place. Do people in the PO have PM training or PM experience, and vice versa?

4.2 Improving Network Communications Structures

This section considers organizational communications networks and how to improve them when savings in cost or time per day-to-day transaction could yield large savings due to repetition. It will also consider ways to adapt the networks to include PM features and make comparisons between the old and new or planned structures.

When an organization's documented or expected lines of communications do not correspond to reality, time and energy may be wasted. Oehmen et al (2015) give an example of a project manager who studied network communications within the organization and to suppliers to better understand the "real" communications pathways for the project. When there is a gap between the expected and real communications pathways, more resources may be needed to manage project communications. For the organization as a whole, when only a few people with "organization awareness" know the "best" lines of communications, bringing the expected and actual lines of communication closer together could improve effectiveness.

To close the gap between actual and expected communications in an organization, one could study the patterns of communications (e.g. emails volumes) in graph form. The vertices of the graph are the people or units under consideration (and may include external parties) and vertices are joined by an edge with weight the actual minus expected volume of communications between the two parties, or by directed edges if the direction of communication is important. If there is a path between two vertices whose volume is very large, it may be that this path is more efficient than the expected path. The organization could change its communications protocols to match the reality and ensure that the change is recognized so that all communications follow this newly sanctioned pattern. On the other hand, if the goal is for actual and expected volumes to match (e.g. in a spy ring each spy only meets the spy who provides information and the spy who receives information) then further study will be needed to identify the barriers that are preventing the expected patterns from appearing.

The models used by Hurwicz (1986), Mount and Reiter (1990), Radner (1993) and Reiter (1996) provided means to quantify properties of structures of interest. This allowed them to compare classes of structures and determine if one class outperformed another. Their models can be interpreted as computing the time for information to enter a system, be processed step by step by agents until a single result is produced and sent to a decision-maker. In their models, each step of the process takes one unit of time, while communications between steps are instantaneous and have zero cost and the capacity of each agent is limited and equal. Mount and Reiter (2002) noted communication between agents in close proximity can be less costly or more efficient than communication between agents who are in some sense distant from one another. They attribute this to various factors including learning curves and organizational memory. Easley and Kleinberg (2006) note a pattern that is emerging is extensive communications within large groups of an organization, with only a few links between groups. They also note that in situations where a person outside several groups that do not communicate directly communicates with the group's innovation is sometimes achieved through synthesis of the ideas from the separate groups.

If communications in an organization composed of large groups, with no or only a few links between dissimilar groups, are inadequate, adding a person who will provide between-group communications may improve communications and foster innovation. This between-groups communicator plays a role similar to a project manager (internal or external) who is often the link between Senior Management and external partners on the one hand and internal units vital to the project on the other. Between-group communications may require more time, cost more or have lower capacity than in-group communications (e.g. summarizing for senior management, explaining acronyms, paying for translation). To model such a change to the communications graph, add a vertex to represent the additional person and join it to all the other groups. Depending on the area of study, the edges will be assigned the costs, time or capacity reflective of the effort to communicate between dissimilar groups in the organization. With an appropriate algorithm, one can determine the minimum cost, shortest time or maximum flow. If the results support adding such a person (or persons) it may make sense to locate them within one of the groups, lowering the cost and time to communicate to that particular group.

This section touched on some of the components needed to model and compare the efficiency of PM and SBM practices. In particular, graph theory arguments were used to replicate the result that the proportion of managerial positions must grow as the size of the firm grows. In addition, variables derived from an increased distance and related to PM practices were presented; and finally models to compare the efficiency of communication networks, for different situations within the same structure and for different structures under the same situation, were outlined. Further study will be needed to determine if there are classes of PM structures that outperform the related classes of SBM structures.

5. Conclusion

Many operational management problems are solved with graph theory tools. The greater distance between resources and needs characterizing the global economy could be a determinant factor of increasing demand for PM services at the organizational level. Graph models provide a quantifiable approach to optimizing organizational communications networks. Modifying this model to incorporate PM features could provide a quantifiable comparison of organizational structures that use SBM with those that use a PM approach. This is very exploratory.

In Mintzberg (1979), the various parts of an organization “are joined together by different flows – of authority, of work material, of information, and of decision processes (themselves informational)” (p.35). Creating value in a measurable way is a condition of survival for organizations that are firms; graph theory provides means of meaningful optimization over complex structures of flows associated with coordination costs and motivation costs, or, in the broad sense used by Radner (1992), with the costs of management tasks. Beyond differences in the ways of breaking down organizations into parts, both Mintzberg and Radner place R&D beside the “operating core” (Mintzberg (1992), p.19) or the “production units” (Radner (1992), p.1392), classifying R&D with other support services like payroll, legal council, cafeteria… For firms in the new economy in particular and for a significant portion of globalized firms, inventing new things becomes the operating core or the production activity. It is a different paradigm with organizational challenges more analogous of the historical context in which PM has emerged than the SBM historical context. Could we then conjecture that PM principles will do a better job at minimizing agency costs, at handling motivation and at making R&D teams more compact, and more effective? Again, graph theory representations could be useful for identifying conditions and hypotheses under which it could be so.

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