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When Project Information Flow Becomes Turbulent: Toward an Organizational Reynolds Number

By

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Abstract

When managers try to develop complex products with many interdependent subsystems quickly, the high information processing load this creates can cause organizational failure. There is currently no way for managers to tell when the demands placed upon a project team are great enough that the risk of organizational failure has reached unacceptable levels. Engineers use the Reynolds number in fluid mechanics as a metric that predicts whether the flow of a fluid will be smooth and stable versus turbulent and chaotic. This paper describes an initial attempt to define a similar metric for project information flow, an "organizational Reynolds number" that uses various organization and work process parameters to predict whether a project team is approaching the turbulent information flow regime and is thus at risk of organizational failure.

Motivation

Organizations with limited resources are assigned the challenge of designing high performance products faster than ever before. The high information processing load generated by product complexity, task interdependence, and excessive schedule pressure can overwhelm a project team. Errors, poor decisions, and bad communication can quickly spread through the work processes and project teams, resulting in additional coordination and downstream rework that can cause quality meltdowns and organizational failure.

Project failure can lead to product failure as well. The prototype Lockheed Launch Vehicle called for five-to-one schedule shrinkage from Lockheed's prior military launch vehicles and required outsourcing of a key component to save costs. The vehicle launched four months late and had to be detonated in the atmosphere (Levitt, 1999). The failure was not due to a technical challenge or the use of inexpensive materials; the problem arose from a small cable harness team in Alabama that was under intense time pressure. In the face of frequent changes to the concurrently evolving avionics design, the cables subcontractor became overwhelmed with coordination responsibilities and was unable to complete its task successfully.

If management could accurately diagnose potential areas of failure, it could proactively try to prevent them by changing the design of the organization to handle the increased information load. Engineers use the Reynolds number in fluid mechanics as a metric that predicts whether the flow of a fluid will be smooth and stable (laminar flow) versus unstable and chaotic (turbulent flow). Information flow throughout an organization acts in the same way – sufficient organizational capacity will allow for good information flow through a team while an overwhelmed group will suffer from turbulent information flow and risk total failure. A metric similar to the Reynolds number that could determine if the information flow through an organization was going to be efficient and reliable versus inconsistent and chaotic would help management assess the risk of organizational failure. The goal of this research is as follows:

Use SimVision, an organization simulation framework, to discover a non-dimensional organizational information flow analog to the Reynolds number in fluid mechanics that predicts when an organization is at risk of failure.

Points of Departure

Contingency Theory and Organization Design

Organization design is the process of fitting the structure and policies of an organization with the environment and technology with which it interacts in order to achieve its goals. Organizations should be designed to be effective, efficient, and viable (Burton and Obel, 1998) over the long term. Galbraith separates organization design choices into five categories: strategy, structure, processes, rewards, and people (Galbraith, 1995). This paper will focus on the structure and processes design choices, which involve the shape of the organization, the hierarchy of authority, and the policies for decision making.

The challenge is designing the organization to succeed in its environment. Contingency theory states that there is no best way to organize, but that all ways to organize are not equally effective. The theory states qualitative rules that have been observed through research involving how companies organize in specific contexts and how organizations with different structures perform in those contexts. For example, empirical research has found that companies engaged in routine, predictable work perform better if they are more centralized and tightly controlled, whereas companies whose tasks have a higher level of uncertainty need to be more decentralized and loosely controlled. The theory has linked design factors such as formalization, structure, lateral processes, and reward systems with environmental factors such as type of industry, level of competition, speed of business, geography, and customer base.

Contingency theory has given us general, qualitative guidelines for organization design, but it fails to predict specifically what will happen in a given situation. No numerical evidence has been given to support or reject various designs. Research cites specific examples of companies that have had success with certain organizational characteristics and, from these case studies, researchers draw conclusions and theorize over other possible situations. Obviously, it is difficult to obtain quantitative results when both the inputs and outcomes of an experiment are qualitative in nature.

An Information Processing View of Organizations

In 1974, Jay Galbraith introduced an information processing view of organizations. The model abstracts work as simply a quantity of information to be processed, and argues that the greater the uncertainty of the task, the greater the amount of information must be processed to complete it. Galbraith defines uncertainty as "the difference between the amount of information required to perform the task and the amount of information already possessed by the organization" (Galbraith, 1975, p 36). This means that routine tasks which have little uncertainty contain less information to be processed, or take less time to complete than a task with high uncertainty.

An organization can then be thought of as an information processing machine with a capacity to process information. The capacity of an organization depends on its structure, decision making policies, and the availability, skill level, and experience of its workers. An organization should be designed to have sufficient capacity to satisfy the demands placed upon it or it is at risk of organizational failure.

Galbraith offered several dimensions of an organization than can be altered to reduce the demand for information processing or to increase information processing capability, although they are not without cost. For example slack resources, in the form of extra workers, more generous budgets, or looser deadlines, can be added to reduce the need for information processing, but the organization then incurs the cost of the incremental resources or schedule. An organization could also decentralize decision making, removing the communication requirement between lower level workers and management. However, this can result in poorer decision making and the loss of management control if lower level managers lack the knowledge or perspective to make good decisions on their own.

SimVision

Galbraith did not attempt to quantify either the capacity of an organization or the information processing requirements of the work; he only provided qualitative guidelines to use in various situations. The SimVision® simulation framework, developed by the Virtual Design Team research group at Stanford (Jin and Levitt, 1996) and commercialized by Vité Corporation in 1996 (www.vite.com), quantifies and extends Galbraith's theory and models the organization as an information processing machine.

SimVision integrates an organization made up of individual participants organized into a structure, with a task work breakdown structure created to model the work to be done by the organization. The participants each have a skill set, experience level, and capacity to do work. The work breakdown structure consist of tasks that each have a skill requirement and volume of information to be processed. SimVision allows sequential and rework dependencies and information exchange requirements between tasks to be explicitly defined. Each task is assigned to a responsible participant. When an uncertainty arises during a task, an "exception" is generated and the responsible participant refers the decision up the organization's hierarchy. In a highly centralized structure, more decisions are made by management than subordinates; the opposite is true for a structure with low centralization. A decision is made to ignore the exception, quick fix it, or rework part of the task.

SimVision models four types of work: direct, rework, communication, and wait time. Direct work is the volume of information required to complete each task assuming that there are no exceptions. Rework, communication, and wait time are classified as indirect work that arises when exceptions are generated. A Monte Carlo simulation is run combining the specific project tasks and team structure characteristics entered into the model with generic, low-level team participant behavior data created from years of research by the Virtual Design Team group. The simulator predicts schedule, participant backlog, total cost, and computes several measures of process quality.

SimVision is able to accurately reproduce the real effects of backlogged teams and has been extensively validated on numerous projects over the last ten years. Its greatest success was the prediction of the Lockheed Launch Vehicle failure described earlier. The Virtual Design Team's model of the Lockheed organization showed that the concurrent work process placed additional coordination responsibility upon the cables subteam, causing significant backlog. This led to both the four-month schedule delay as well as the quality breakdown that required the vehicle to be detonated. More recently, SimVision has also become a popular tool for university researchers to run "virtual experiments" (Carroll and Burton, 2000; Wong and Burton, 2000).

SimVision's ability to quantify the capacity of an organization and the work to be processed makes it ideal for this research. In the search for an organizational Reynolds number, the capacity of the team and the volume of direct work are held constant, while the interdependency of the work process and the rate at which exceptions occur within tasks increase. As the organization is incrementally overwhelmed with indirect work, the effect on the total duration of the project is examined.

The Reynolds Number

The Reynolds number (Re) in fluid mechanics inspired the concept of a similar phase boundary for organizations that demarcates when a system changes from in-control to out-of-control. The Reynolds number is a non-dimensional number that predicts when fluid changes from laminar to turbulent flow. The Reynolds number equals inertia divided by viscosity; the inertia term is dependent upon the velocity of the fluid and the diameter of the pipe, while the viscosity term is a measure of resistance to internal shear friction forces and is specific to each fluid. A value of the Reynolds Number less than 2000 indicates laminar flow and a value over 2300 indicates turbulent flow; in between these limits, the fluid flow is unstable and might flow in either state.

At low velocity (Re<2000), fluid flows in a straight line, generating only small eddies that are damped out rapidly. In this state, the energy loss to the system is directly proportional to the velocity of the liquid. As the velocity of the fluid increases, the fluid passes through an unstable transition period (2000<Re<2300), where the slightest disturbance instigates turbulent flow—eddies that grow and are not damped out by viscous forces internal to the fluid. At higher velocities (Re>2300), the small eddies propagate and fluid flow is turbulent, or chaotic, with continual fluctuations in both velocity and pressure. The energy loss due to friction in turbulent flow is immediately increased and now varies with the square of the velocity.

Suppose that information flow throughout an organization is analogous to fluid flowing through a pipe. If the capacity of the organization is large enough to handle the information flowing through it, indirect work (rework, communication, wait time) should vary with the rate of information to be processed. As more work is forced upon the organization, the amount of time spent on rework and coordination increases, but the additional indirect work is proportional to the increased work volume.

However, when an organization becomes overwhelmed and demand exceeds capacity, information flow throughout the organization stagnates. In this turbulent state, organizational performance and efficiency decrease quickly. Indirect work increases exponentially rather than linearly with further increases in the amount of work required, and the organization is at serious risk of failure.

Does the information flow through an organization change from laminar to turbulent at a predictable point? If an organizational Reynolds number exists, which variables and characteristics would define the capacity of the organization and the demand of the information to be processed? Piping networks are designed to minimize energy loss by avoiding turbulent flow. Organizations should then be designed to process the greatest amount of work in the shortest time period possible without risking chaotic information flow.

Approach and Methods

When Organizations Become Overwhelmed

Each participant in SimVision can be thought of as an information processing machine. Work to be done is placed into a participant’s inbox, where it enters a queue and waits to be processed. If the length of a participant's inbox grows, he falls behind and is unable to complete his tasks on schedule. A backlogged participant is less likely to attend meetings and answer requests by others for information, and often fails to receive the information necessary to complete his own tasks. This behavior leads to poor decision making and increases the probability that the participant will cause exceptions in the future.

As a participant falls further and further behind, he delays others and causes the overall work process quality to deteriorate and errors to spread throughout the organization. Other participants whose tasks rely on information from the backlogged participant suffer as well. Management participant backlog has an even more drastic effect as subordinate participants have to wait for managers to make decisions. If they are forced to wait long enough, they make the decision by default using their best judgment. This results in poorer quality decisions causing costly downstream rework.

Organizations want to minimize the amount of indirect work necessary to complete a project. If participant backlog is not controlled, exceptions and indirect work can build upon each other and spiral out of control. Due to shared resources and dependent tasks, these problems can quickly spread throughout an entire organization. Organizational bottlenecks can evolve into organizational chaos. There is a clear "information flow turbulence" analog here to eddies propagating through a fluid flow field, rather than being damped out by viscous forces.

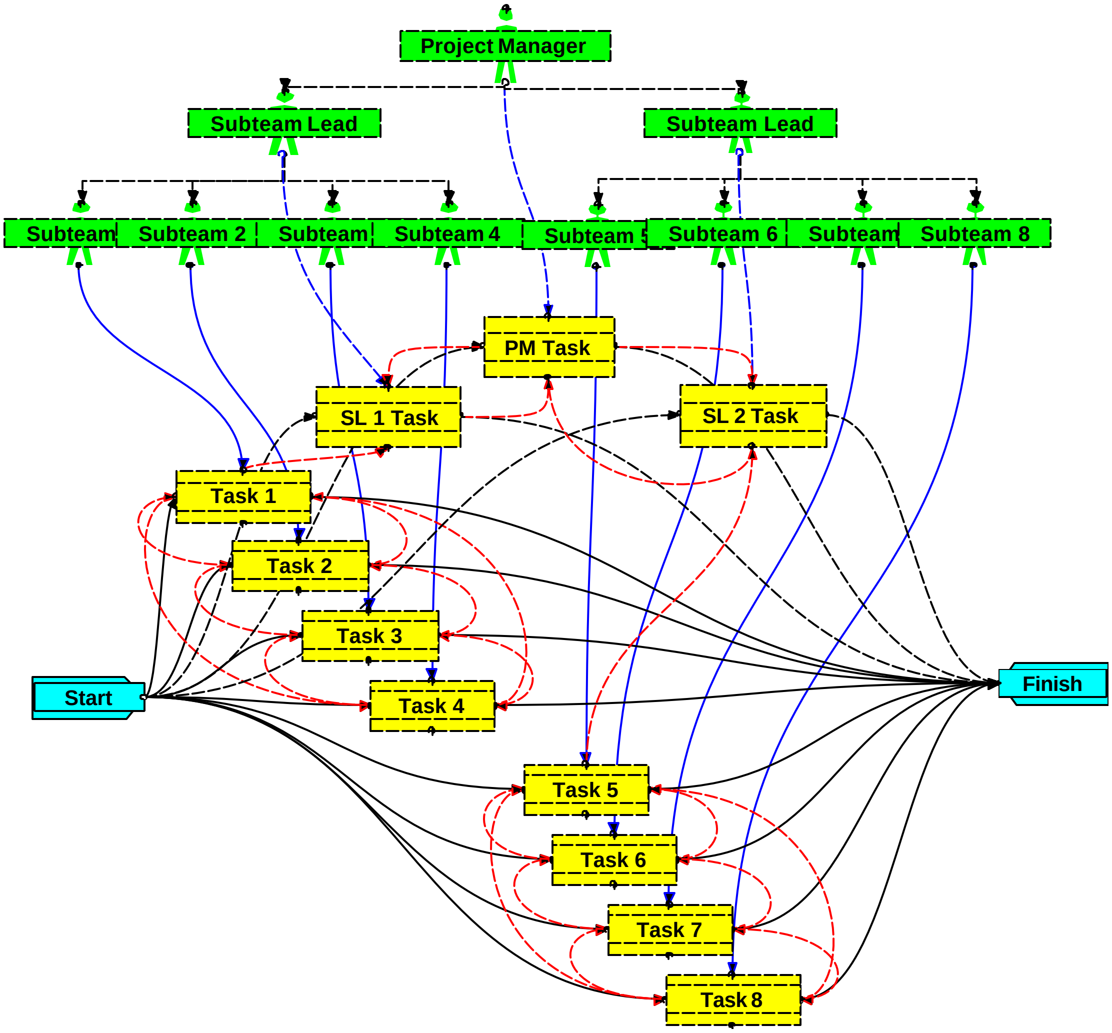
SimVision Model

In order to search for an organizational Reynolds number, we created a simple project team and work process in SimVision, shown in *Figure 1*. The project team consists of one project manager, two subteam leaders, and eight subteam participants. Each participant is responsible for one 40-day task and all tasks start in parallel with each other. The red-dashed lines connecting tasks are “rework dependency links” that cause an exception in one task to create an exception in another dependent task. The level of interdependency of the work process is measured by the “dependency ratio” (DR), a ratio of the number of rework links per task. The baseline model has two rework links per task (DR 2).

If the model were run with a zero probability of exceptions, the project would take 40 days to complete. This is the direct work specified by the task volumes. However, with a positive probability of exceptions, indirect work will be required in the forms of rework, communication, and wait time. The total duration will then be the 40 days of direct work plus time to process the amount indirect work. Increasing the probability of exception, the level of task uncertainty in Galbraith’s framework, increases the amount of information to be processed by the organization.

Each of the twelve experimental scenarios described in the following section uses the same organization structure and work breakdown structure. Each scenario is specified by the level of centralization used (low, medium, high) and the failure dependency ratio. For each scenario, several cases were run with increasing probability of exceptions. By keeping the capacity of the organization constant, we were able to compare the increase in indirect work with the marginal increase in the difficulty/uncertainty in the work process represented by the increased error probability.

Figure 1: SimVision Model



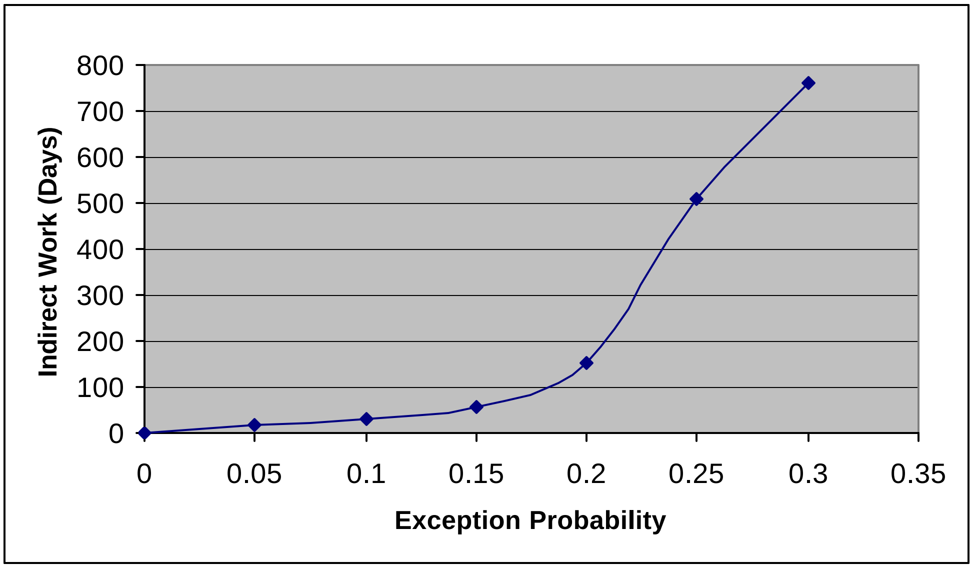
- The green characters represent participants and the yellow rectangles represent tasks.
- Each participant is responsible for one task. A blue line represents this assignment..
- The dashed red lines are dependency links (DR = 2).

Simulation Data and Analysis

Baseline Scenario

Figure 2 illustrates the concept of clear delineation between laminar and turbulent behavior. Each data point represents a single simulation with an initial error probability plotted against the number of days of indirect work required to complete the project. With an error probability of 0.05, the project will take 57 total days to complete; 40 days of direct work and 17 days of indirect work (rework, communication, and wait time). As the probability of exceptions is increased, additional indirect work is required to complete the project. The slope of the line represents the incremental increase in the amount of indirect work versus the increase in the exception probability. The baseline scenario has DR = 2 and medium centralization.

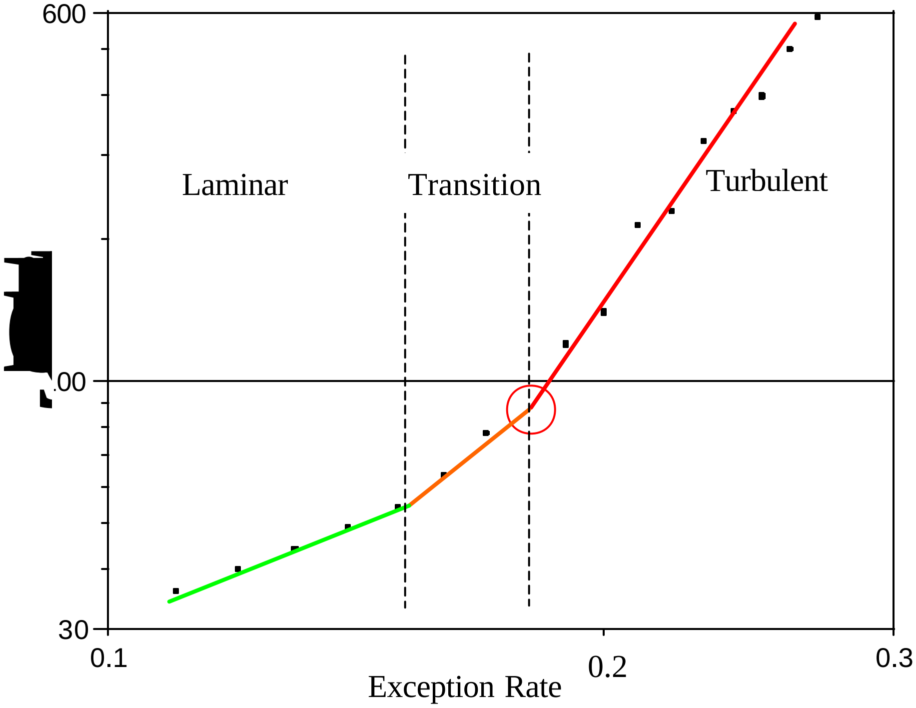
Figure 2: Baseline Scenario
DR=2, Medium Centralization



The curve increases linearly until an exception probability of between 0.15 and 0.2, at which point the curve increases exponentially. Information flows smoothly through the project team while the effect of an increase in the error rate on the amount of indirect work is constant. During exponential growth, the team is in a turbulent state and the amount of indirect work needed to complete the project dwarfs the amount of initial work required. Managers clearly want to minimize the amount of costly indirect work, and want to keep their projects out of the turbulent region. For example, an increase in error probability from 0.1 to 0.15 would cost about 20 days of indirect work, while an increase in error probability from 0.2 to 0.25 would cost about 250 days of indirect work and dramatically increase the risk of project failure.

Figure 3 uses the same simulation model as *Figure 2* with more simulation runs around the point of inflection.

Figure 3: Baseline Scenario (Logarithmic)
DR=2, Medium Centralization



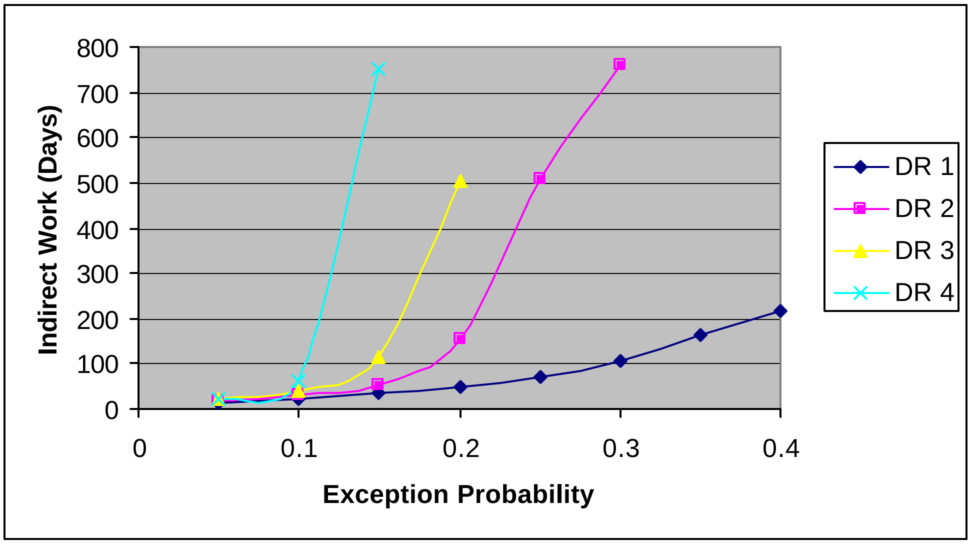
The data points graphed are in increments of an increase in error probability of 0.01 and they are plotted on a logarithmic scale to more clearly show the definition between the laminar, transition, and turbulent regions. The organizational Reynolds number occurs at the point on the logarithmic graph at which the change in slope is greatest (also referred to as the point of inflection), circled on *Figure 3*. As the exception rate increases, other variables are also impacted by turbulent flow. *Appendix 1* and *Appendix 2* show that both the number of exceptions and the cost of indirect work increase dramatically in the turbulent region and follow a similar curve to *Figure 2*.

Level of Dependency

The experiment was repeated with rework links per task of 1, 3, and 4. The error rate at which the slope discontinuity occurred in each scenario was determined from visual inspection of a logarithmic plot like *Figure 3*. The exception rates from DR 1 to DR 4 are 0.26, 0.18, 0.13, and 0.1 respectively. The more dependent the work process, the less uncertainty is required to case turbulent flow.

Figure 4 shows all four scenarios plotted against each other. The higher the rework link ratio, the lower the exception probability at which the discontinuity occurred and the steeper the slope of the turbulent region. In the DR 4 scenario, the simulator crashes at an exception rate of 0.15; so many exceptions are generated that the project does not complete. This is shown with an arbitrarily high representative data point on the graph.

Figure 4: Level of Dependency
Medium Centralization

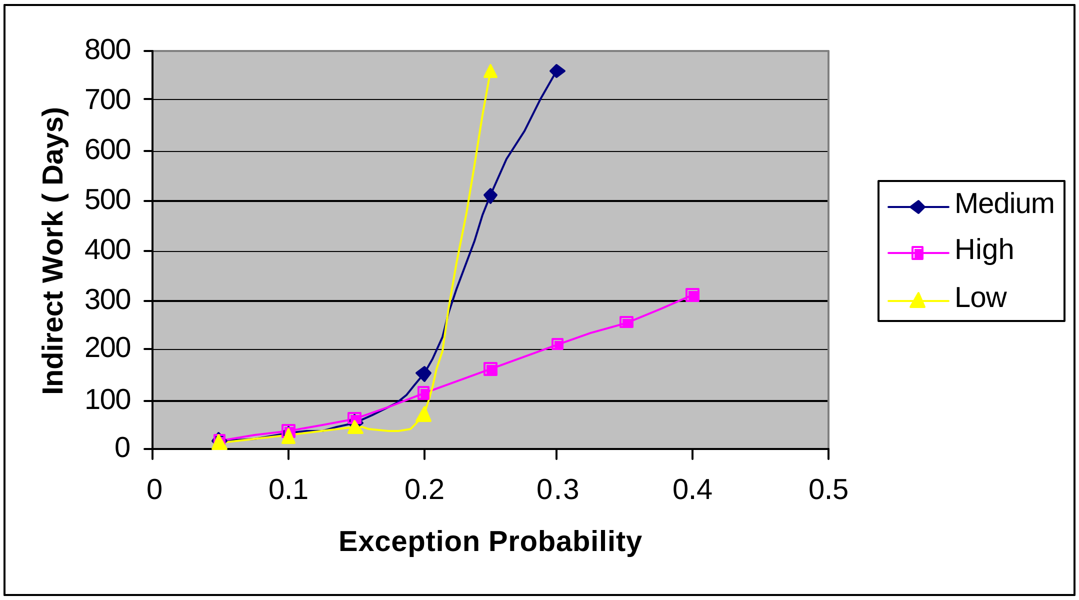


Level of Centralization

The centralization level of an organization determines at which level in the hierarchy most decisions are made. In a highly centralized structure, more decisions are made by management, who tend to demand higher quality and order more rework than subordinates. A team with a low level of centralization tends to make decisions at the team level requiring less communication, although subordinates have the tendency to ignore errors rather than taking the time to fix them.

The scenarios mentioned in the previous section were repeated with low and high centralization for a total of 12 experiments. *Figure 5* shows DR 2 run with low, medium, and high centralization. The high centralization scenario changes slope around 0.15, although the slope only increases gradually. The low centralization scenario has a linear slope until 0.2, but the simulator does not complete at 0.25.

Figure 5: Level of Centralization (DR =2)



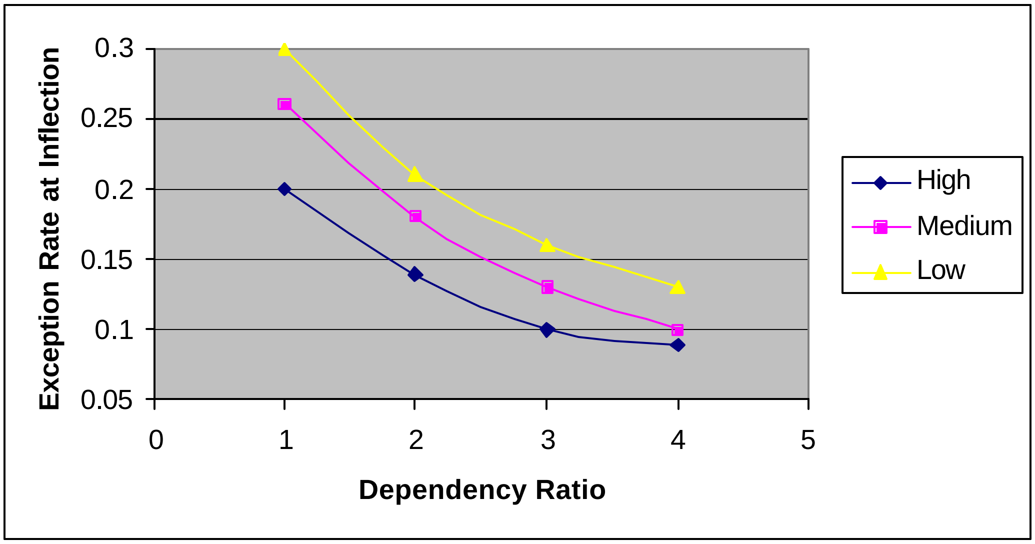
These relationships are observed for all dependency ratios. The previous finding of a steeper slope and lower exception rate at the inflection point also holds when comparing scenarios with low or high centralization. As predicted by Galbraith, low centralization increases the capacity of the team to operate under stressful situations by extending the turbulent region to a higher error rate; however, there is no transition period before the turbulent region begins. High centralization scenarios change slope earlier than the low or medium centralization scenarios, but the slope change is not nearly as drastic because exceptions are controlled by management requiring rework. In the DR 1 and DR 2 high centralization scenarios, turbulent behavior is hardly noticeable. In the laminar region, high centralization scenarios take the longest period of time due to rework required by management.

The Organizational Reynolds Number

The goal of these experiments was to find an organizational Reynolds number (OR_N) that would predict the “edge of chaos” – the point at which information flow turns turbulent – for each scenario using the dependency ratio, level of centralization, and the exception rate at the point of inflection. The data gathered for the 12 scenarios is in *Appendix 3*. In order to look for a relationship between the 12 scenarios, the data were plotted with the dependency ratio versus the exception rate with different colored points classifying the level of centralization (*Figure 6*).

The objective was to find a Reynolds number that is identical for each scenario at the inflection point. Visual inspection of *Figure 6* shows that the three lines connecting the scenarios with the same level of centralization all have approximately the same slope. *Figure 6* was plotted with the x axis on a logarithmic scale (*Appendix 5*) and the equation of the medium centralization line is approximately y = 0.26 – 0.28 * Log (x), where y is the exception rate and x is the dependency ratio.

Figure 6: Inflection Points Plotted for 12 Scenarios



The following equation, based on the equation of the medium centralization line with an added centralization factor, was placed into an Excel spreadsheet (*Appendix 6*) along with the data for the 12 scenarios:

Point of Inflection / Centralization Factor + Slope Factor * Log (DR) = constant

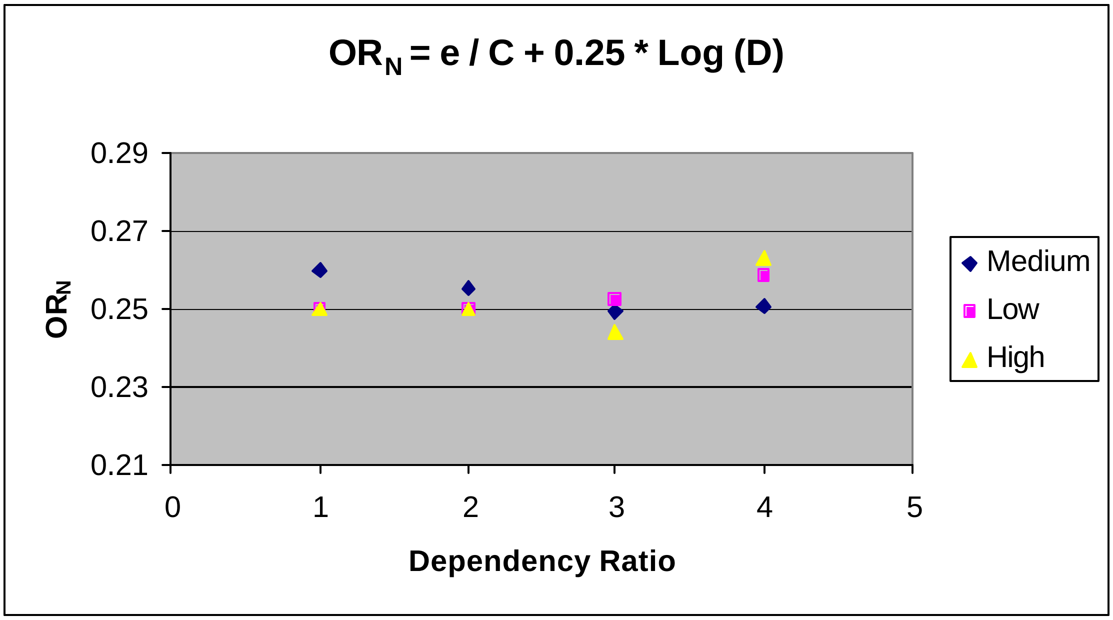
Various values were tested for the low, medium, and high centralization factors as well as the slope factor. The goal was to obtain a constant with minimum variation throughout the 12 scenarios. The initial value tested for slope factor was 0.28 (the slope of the medium centralization line), and the value for medium centralization was set at 1.
The following equation was found:

$$OR_N = e/C + 0.25 * Log(D) = 0.25$$

e: exception rate at inflection, C: centralization factor (low=1.2, medium=1, high=0.8),
D: dependency ratio (rework links per task)

The computed OR_N at the "edge of chaos" for each of the twelve scenarios occurs within 0.01 of the value 0.25 (*Figure 7*). This suggests that, as the OR_N for an organization approaches 0.25, it is at risk of failure, and a value above 0.25 signals that turbulent information flow has begun to occur.

Figure 7: OR_N at the "Edge of Chaos"



Conclusion

This research is an initial attempt to quantify the work process and organizational characteristics that contribute to an organizational Reynolds number. Using the SimVision simulation environment, we were able to discover a relationship that includes the probability of errors in tasks, the degree of task interdependence, and level of centralization that predicts the "edge of chaos" to occur at an organizational Reynolds number of 0.25.

The managerial implication of an organizational Reynolds number is that it can predict the level of organizational risk for a project given its team characteristics and workflow parameters. If the estimated OR_N for a project approaches the turbulent region, management can proactively mitigate the risk by changing project parameters before turbulent behavior occurs.

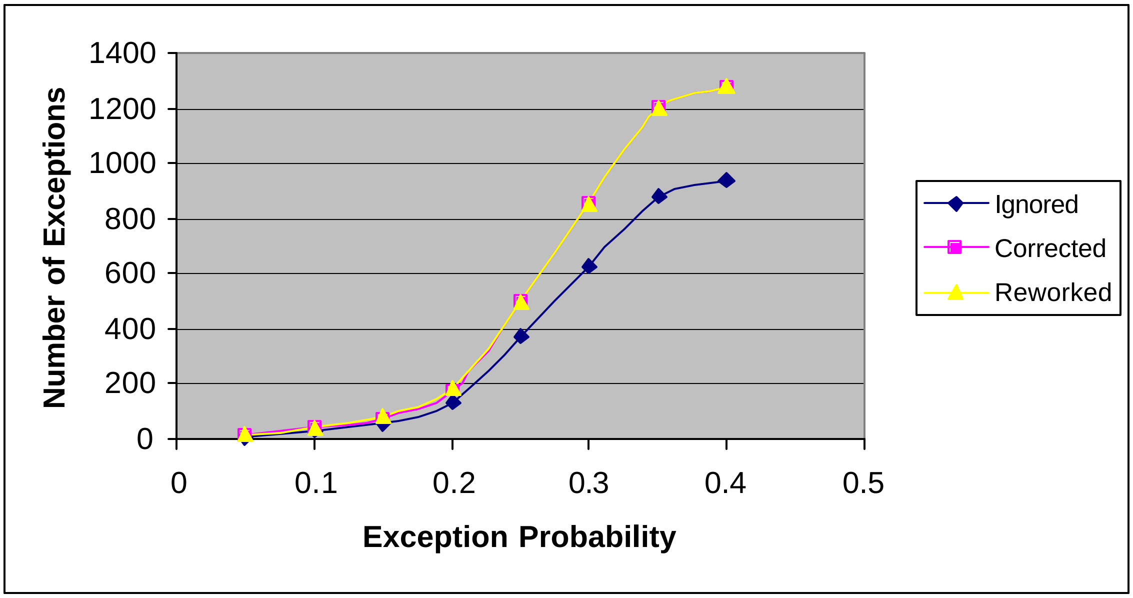
Project managers can estimate an OR_N for their organization by creating a work flow diagram to approximate the degree of subtask interdependency and by assuming an error rate that is justified by the level of task uncertainty. Routine tasks typically have a 0.05 probability of exceptions, and highly innovative tasks have a 0.15 probability (Jin and Levitt, 1996). Centralization can be determined by who makes decisions on the project team: low for most decisions made by workers, medium for most decisions made by first level supervisors, and high for most decisions made by the project manager.

If the estimated OR_N approaches 0.25, a manager should monitor the situation carefully and avoid any changes to the project plan, such as increasing product complexity or shortening the schedule, that would bring the organization closer to the turbulent region. If the OR_N exceeds 0.25, the process parameters should be immediately changed to bring the workflow into the laminar regime. Possible interventions could include decreasing the level of centralization or placing tasks in series to decrease the level of interdependency.

Besides a computed OR_N, managers also have other signs that could hint at turbulent flow. A sharp increase in exceptions generated, management backlog, participants missing meetings, and an increase in indirect work might mean that the project is spinning out of control. Relieving schedule pressure, increasing the level of decision making, and ordering more rework can bring the project back into control.

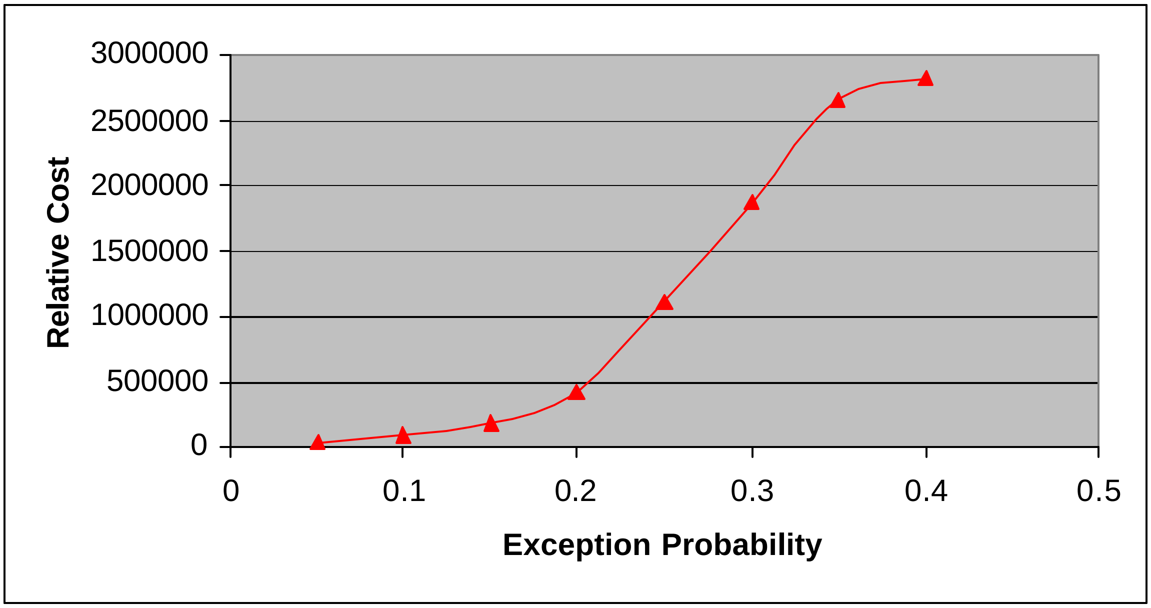
Future research should examine the effect of other organizational viscosity and information flow inertia variables on the OR_N. Initial work has been done on span of control, level of formalization, and availability of slack resources. Other potential variables are skill level, team experience, and participant multitasking. The next step would be to validate and calibrate the OR_N using SimVision models of real project team data and comparing it to the actual performance data.

Appendix 1: Number of Exceptions for the Baseline Scenario



- Exceptions can be either ignored, corrected, or reworked. The total number of exceptions generated is the sum of the three shown here.

Appendix 2: Indirect Work Cost for the Baseline Scenario



- The actual cost numbers are irrelevant to the simulation and the experiment.

Appendix 3: Data at the Point of Inflection for All Scenarios

Dependencies / Task	Centralization	Exception Rate	Indirect Work	Indirect / Direct Work	Computed Reynolds
1	Medium	0.26	75	1.88	0.26
2	Medium	0.18	86	2.15	0.26
3	Medium	0.13	71	1.78	0.25
4	Medium	0.1	61	1.53	0.25
1	Low	0.3	66	1.65	0.25
2	Low	0.21	71	1.78	0.25
3	Low	0.16	73	1.83	0.25
4	Low	0.13	74	1.85	0.26
1	High	0.2	56	1.40	0.25
2	High	0.14	55	1.38	0.25
3	High	0.1	47	1.18	0.24
4	High	0.09	53	1.33	0.26

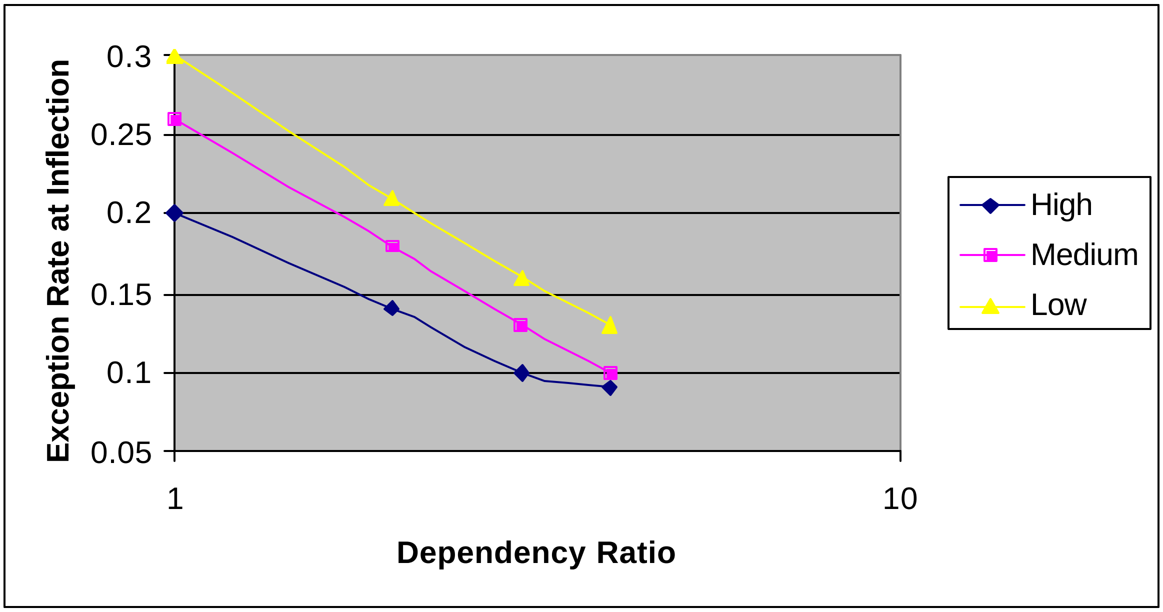
- The indirect work is the amount of indirect work in the simulation at the point of slope change. The Indirect / Direct work ratio is this number divided by the amount of direct work (40 days).

Appendix 4: Days of Indirect Work at a Exception Probability

FR	Centralization	e = 0.05	e = 0.1	e = 0.15	e = 0.2	e = 0.25	e = 0.3	e = 0.35	e = 0.40
1	Medium	12	23	35	50	69	107	163	216
2	Medium	17	32	55	153	510	760	***	***
3	Medium	20	41	116	503	***	***	***	***
4	Medium	24	61	***	***	***	***	***	***
1	Low	10	19	30	42	54	68	85	111
2	Low	13	27	44	71	***	***	***	***
3	Low	17	35	64	***	***	***	***	***
4	Low	20	45	***	***	***	***	***	***
1	High	13	25	39	55	75	103	133	149
2	High	17	34	61	113	162	210	254	307
3	High	21	48	97	175	310	379	477	508
4	High	25	66	189	395	614	810	968	***

- *** indicates that the simulation crashes. This happens when so much rework is generated that the project never finishes in the simulation.

Appendix 5: Exception Rate versus Dependency Ratio for All Scenarios (X –axis Logarithmic)



- Equation of medium centralization line as taken from the two points: (2, 0.18), (3, 0.13); $y = 0.26 – 0.28 * \text{Log}(x)$

Appendix 6: Excel Worksheet for Testing of Organization Reynolds Number

Worksheet to test equation of form: Point of Inflection / Centralization Factor + Slope Factor * Log (DR) = constant

derived from equation of line from Appendix 5 for medium centralization: y = 0.26 - 0.28 Log (x), or Point of Inflection + 0.28 Log (DR) = 0.26

Centralization	Point of Inflection	Inflection / Cent Factor	DR	Log (DR)	Slope Factor *Log(DR)	Inflection/Cent Factor + Slope Factor * Log(DR)	Deviation from mean
Med	0.26	0.26	1	0.000	0.000	0.26	0.01
Med	0.18	0.18	2	0.301	0.075	0.26	0.00
Med	0.13	0.13	3	0.477	0.119	0.25	0.00
Med	0.1	0.1	4	0.602	0.151	0.25	0.00
Low	0.3	0.250	1	0.000	0.000	0.25	0.00
Low	0.21	0.175	2	0.301	0.075	0.25	0.00
Low	0.16	0.133	3	0.477	0.119	0.25	0.00
Low	0.13	0.108	4	0.602	0.151	0.26	0.01
High	0.2	0.250	1	0.000	0.000	0.25	0.00
High	0.14	0.175	2	0.301	0.075	0.25	0.00
High	0.1	0.125	3	0.477	0.119	0.24	0.01
High	0.09	0.113	4	0.602	0.151	0.26	0.01
						mean = 0.25	0.051

Centralization Factor	
Low	1.2
Med	1
High	0.8

Slope Factor	0.25

Equation shown: Point of Inflection / Cent Factor + 0.25 * Log (DR) = 0.25
where Cent Factor: Low = 1.2, Medium = 1, High = 0.8

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