Numerical Evaluation of Product Development Processes

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1. Introduction

The management of new product development (NPD) processes is a continual challenge facing organizations that develop complex, innovative products. While market trends are forcing shorter product development times in order to meet time-to-market (TTM) goals, companies are trying to develop mechanisms to streamline their NPD processes. One approach that has provided much success towards achieving shorter TTM is concurrent engineering (Winner et al., 1988; Clark and Fujimoto, 1991; Blackburn, 1991; Wheelwright and Clark, 1992; Smith and Reinersten, 1991). Concurrent engineering (CE) can broadly be defined as the integration of inter-related functions at the outset of the product development process in order to minimize risk and reduce effort downstream in the process, and to better meet customers' needs (Winner et al., 1988). Multi-functional teams, concurrency of product/process development, integration tools, information technologies, and process coordination are among the elements that enable CE to improve the performance of the product development process (Blackburn, 1991). The traditional NPD process suffers many setbacks. This process evolves in a sequential fashion, where phases follow one another serially, each one dominated by a single functional role. There is little or no cross-communication among various functions, and information generated from one activity gets handed off to the next only after its completion. The commonly encountered problems with this type of process are increased downstream effort, process span time, i.e., the start to finish time of the process, and costs.

In order to study and evaluate the performance of CE and sequential NPD processes, a new approach is used based on an existing mathematical technique called the expected payoff method, which is the basis of decision theory. Under this framework, the mathematics which describe the micro-processes, such as information sharing between team members and overlapping of activities, and their relationships with the macro-process performance in terms of expected payoff (where the macro-process is the overall development process), are described. Network diagrams are presented as a formalism for expressing product development processes. The fundamental concept of the model is based on the premise that team members make decisions or choose actions that maximize the payoff (utility or usefulness) that their actions bring to the team. Team members must obtain, process, and communicate information to one another to make decisions that will optimize their performance.

This chapter is organized as follows. Section 2 discusses the existing literature, and highlights the contributions of the research. Section 3 explains the characteristics of NPD processes. In Section 4, the expected payoff method is described and the results of the mathematical analysis are presented. The results are detailed in Section 5, and in Section 6, conclusions and paths for future research are presented.

2. Literature review

In this section, a review of the relevant theoretical and analytical research is presented. Krishnan et al. (1997) developed a deterministic model based on properties of the design process that help to determine when and how two development activities should be overlapped (Figure 1). These properties are defined as 'upstream information evolution' and 'downstream iteration sensitivity'. The former is the rate at which upstream information converges to a final solution, and the information is modeled as an interval that gets refined over time. Sensitivity describes how vulnerable the downstream activity is to any changes in the upstream information, and is defined by the time needed by the downstream activity to incorporate the changes, which represents rework. Different patterns of information exchange between two activities, represented by the arrows in the diagram, are studied.
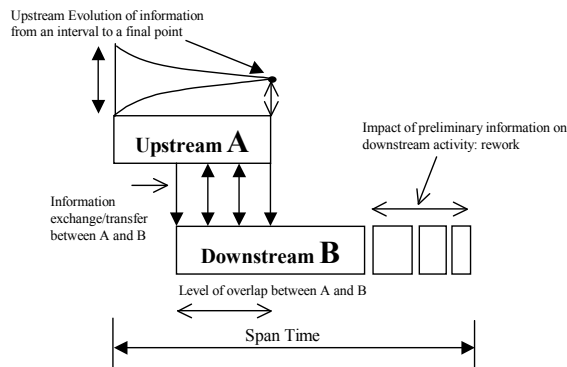
Fig. 1. Krishnan et al.'s model.

The authors address the overlapping problem by studying how values of the two properties determine the extent to which overlapping is appropriate between the dependent activities, A and B, and consequently how the span time is affected. Various overlapping policies between the upstream and downstream activities are examined based on varying the values of these two properties, and an integer program is developed to minimize span time.

Loch and Terwiesch (1998) have developed an analytical model of CE that considers the overlapping of two sequentially dependent activities, an upstream product design activity, and a downstream process design activity. The authors study the trade-offs between the downstream activity using upstream preliminary information to overlap activities, and the corresponding delay this might cause in terms of downstream rework. They suggest that when engineering changes (EC) arise during the product design, this poses the risk of redoing the overlapped work of the downstream activity, and this can be significant if the dependency between the two activities is high. They propose that communication during

overlapping can reduce rework effects, but at the cost of communication time. They also use the concepts of evolution and sensitivity.

Yassine et al. (1999) have studied the CE problem of overlapping activities through a decision analytic framework. Using a probabilistic model consisting of an upstream activity and a downstream activity, their methodology finds the optimal overlapping policy based on the study of independent, dependent, and interdependent activities, described as the information structure of a process. A schedule of when to transfer information based on the information structures can fall under one of three categories: sequential, partial overlapping, and concurrent. Sequential transfer of information takes place for dependent activities. Partial overlapping can take place for either dependent or interdependent activities. In both cases, however, the information exchange/transfer must appropriately minimize the risk of downstream rework in the event of a change in the upstream activity. A concurrent schedule can take place when the activities are independent; since neither requires information from the other to proceed, they may be executed in parallel.

Ha and Porteus (1995) developed a simple model that proposes the optimal policy for the frequency and timing of progress reviews in an overlapped process. The authors study two overlapped, interdependent activities, an upstream design activity and a downstream process activity. In contrast to sequentially dependent activities, the nature of interdependent activities requires team members to communicate frequently. They develop a dynamic program that shows that, in order for overlapped activities to be beneficial, the design activity must be accompanied by progress reviews to minimize the risk of downstream rework and thus span time, and to improve quality. However, these gains are only achieved at the expense of the time and cost spent on communication. Therefore, the frequency of communication or progress reviews must be balanced with the value gained from having them. The optimal policy of reviews minimizes span time by providing sufficient information at the right time, helping to identify potential design problems early.

Different methods to address the problem of overlapping have been suggested in the literature. This research contributes to the existing work by introducing a methodology based on decision theory to study the performance of processes.

3. NPD processes

An information processing view of organizations, and thus of product development, is assumed in this research. From this perspective, the product development process must go through a set of decision-making processes to transform information inputs into information outputs, which are used to develop tangible outputs, i.e., the end product(s) (Clark and Fujimoto, 1991; Galbraith, 1973). Therefore, the focus of the models is on the flow of information as it evolves from the beginning to the end of the development process, making the relationships between development activities more readily apparent.

Product development can be defined as the process of undertaking all the activities and processing the information required to develop a concept for a product up to the product's market introduction. NPD processes may vary from one organization to the next, and as such, there is no one standard process agreed to by all. However, the general steps required

in a product development process are fundamentally similar (Ulrich and Eppinger 2011). The NPD process defined in this study is a generic one which outlines the major steps in product development. It is a summary of the common phases and activities used in many instances in the literature as well as in the case study, and as such, it is a reasonably accepted approach to representing the product development process (Schilling and Will, 1998; Nihtila, 1999; Eastman, 1980).

The NPD process, shown in Figure 2, begins with the development of a concept for a marketable product (Phase A). In this phase, market requirements are determined, new ideas are generated, screened for economic and technical feasibility, and one is selected. In Phase B, 'Definition', a set of specifications to make the product is defined, and the product architecture is developed. Phase C, 'Development', consists of detailed design, physical prototyping, and testing. Finally, in Phase D, 'Implementation', the product volume is ramped up in manufacturing and launched onto the market.
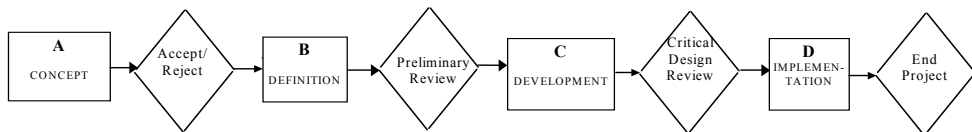

Fig. 2. A schematic diagram for a general stage-gate process with Phases A, B, C, D.

Figure 2 is an example of the traditional NPD process, where the phases are performed sequentially one after the other. Between phases, a one-way dependence is assumed, that is, the downstream phase depends on information generated by the upstream phase, but not vice-versa. This is represented by the uni-directional arrows between phases.

In an NPD process, the relationship between product and process design is mutually interdependent (Tian et al., 1998). This means that the information generated by one or more functions poses contingencies for others, thus, the parameters of the product and the process should be considered simultaneously (Adler 1995). Therefore a higher degree of coordination is required to manage more people collaborating on interdependent activities. In a sequential process, this interdependence is ignored; a dependent relationship is assumed, and this leads to unplanned coordination downstream. While better management of interdependencies does lead to shortened span time as compared to the sequential process, the price is higher cost of upstream effort.

CE uses two main mechanisms to reduce the span time for NPD processes: 1) increased information sharing from the start of a project (functional participation), and 2) overlapping of phases and activities. In a CE process, functional participation takes place through the formation of a team consisting of a representative from each of the functions that contribute to the development of a product. The goal is to make downstream activities easier to perform by releasing preliminary information to them early in the process to allow for overlap of activities. However, due to uncertainty in the early stages of an NPD process, the release of incomplete information to downstream functions may potentially introduce the need for rework should there be a change in upstream information. Thus, potential risks must be carefully examined to ensure that added time and effort are kept to a minimum (Krishnan et al., 1997).

Compared to a sequential approach, CE can decrease span time at the expense of increased interdependencies between activities (sequential to reciprocal). To handle the increased interdependencies, close intensive coordination is required through functional participation. However, this may increase effort.

Figure 3 shows an overlapped CE process. Note that information flows are more frequent than in the sequential case, and they are also bi-directional. Major milestones exist at the same gates as before, and each phase is made up of activities, not shown in the figure.
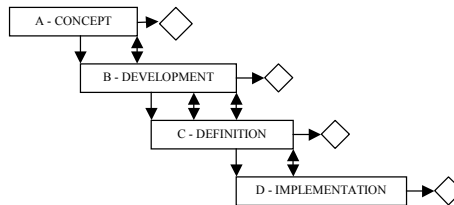

Fig. 3. CE development process.

4. Expected payoff method

In this section, a mathematical approach is described to measure the performance of processes, namely, sequential and CE processes, through the study of macro- and micro-variables. The macro-variable is the expected payoff, while the micro-variables are team interaction and level of overlap. The concepts of information processing and decision-making are presented as the basis of this framework. An information processing view is assumed, so that processes are studied through the way in which several team members perform activities such as acquiring, communicating, and processing information in order to make decisions, which in turn organizes the way activities are executed. Processes and corresponding team activities are modeled via networks of interconnected elements. These elements transform inputs into outputs, and represent people, machines, or other real-world objects. Each network realizes an output which is a measure of process performance, and is used to evaluate and compare processes. The methodology is based on the expected payoff method, a technique used in decision theory. It is applied in the calculation of a simple model of both a sequential and a CE process, and the results are compared.

The principle of the expected payoff method has been applied mainly in the field of economics, management science, and in certain areas of artificial intelligence, with respect to decision-making. In this field, economists study 'the best use of available (limited) resources' (Marschak and Radner, 1972). There has been no use of this method in the evaluation of CE in new product development processes. In an organizational environment, teams are also concerned with making the best use of alternatives or limited resources. The interested reader can find several readings in the literature on the principle of utility theory and its various applications (Marschak and Radner, 1972; Fishburn, 1970; Marschak, 1959; Marschak, 1954; von Neumann and Morgenstern, 1943). The framework developed in this part of the research will compare a simple model of a sequential process to a CE process, and evaluate the two in terms of the total expected payoff.

4.1 Methodology

The approach assumes that individuals in a team work towards achieving common goals with common interests and beliefs, within the constraints of their work, all of which guide their behavior. Given the complexities of such a situation, the problem is allocating appropriate information at the right time, such that team members can make the 'right' decisions which serve to accomplish their common goals (Marschak and Radner, 1972). This chapter will describe the means by which the activities of teams can be described, as well the mathematical analysis which can evaluate team performance, namely, through the use of the expected payoff method. The expected utility or payoff of an action measures the usefulness that an action brings to a person. By combining this with probability theory, decision theory helps a person determine that the action which maximizes his or her expected payoff over all possible actions (from this point forward, for simplicity, the term 'his' will be understood to include 'his/her'). The development of the expected payoff function will be described in detail. Processes can be explicitly represented through network diagrams that illustrate the activities that team members must perform, the inter-relatedness of activities through information requirements, and the communication required among team members (Figure 4). A network realizes a response function, or outcome function, which is based on the actions of the individuals in the organization, and these actions affect the outcome or expected payoff. Among various possible network configurations, the network with the greatest expected payoff is considered optimal.
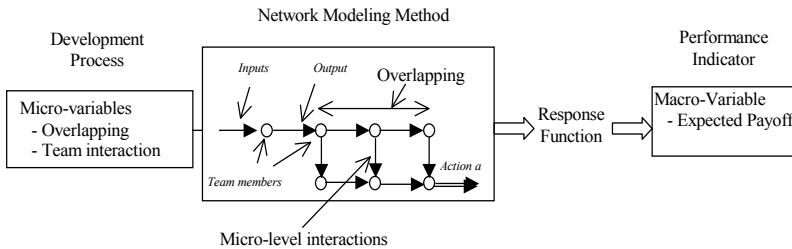

Fig. 4. Expected payoff conceptual model.

An upcoming section describes how network diagrams are constructed, as well as the mathematical tools which compute and evaluate the networks to obtain the total expected payoff.

4.2 Mathematical model: Definition of fundamental quantities

In the following sections, the fundamental quantities of the expected payoff model are defined mathematically.

4.2.1 Actions and outcomes

Faced with a set of alternatives, the decision made by the decision-maker is called his action, a. An action, or decision, can have more than one outcome (or result or consequence). This is denoted as $r = \rho(a)$, where ρ is the outcome function of the action taken. The possible

outcomes also depend on external factors out of the decision-maker's control, which can be called the environment, represented by the variable x. Since an outcome depends on both the action taken and the environment, the outcome function can now be expressed as r = ρ (x, a). Because x is uncertain, the outcome variable r given a is also said to be uncertain. The decision problem now is made up of a set X of alternative states of the environment x, a set A of all possible actions a, a set R of all possible outcomes r, and an outcome function ρ from X x A to r, giving the outcome of each state-action pair, r = ρ (x, a).

4.2.2 Decision rules

The problem of choosing among alternative actions can be generalized by saying that individuals choose among rules of actions or strategies, rather than from a set of possible actions alone. In an organization, rules of action play a very big role in contingency planning, where team members must decide in advance how they will respond to incoming information. This is obviously important in making economic decisions because individuals must be ready to act as soon as they can (e.g. stock brokers). In the context of an engineering firm, if a task is to design and develop a new product and get it to market as quickly as possible, the designers make use of incoming information as soon as they receive it, and they must additionally decide upon how much of it should be transferred to downstream functions, and when.

An action can now be described as a = α (y), where α is the decision function, and y is the information which will be obtained in the future. It should be noted that the information y is not the same as the variable x, the state of the environment, which describes information already received. The expression says that an action a depends upon the information y received.

4.2.3 Information

Information can be generated and obtained by team members through various means, such as through observation, communication, and/or computation. There are two sets of information available to the decision-maker: one is the set X of all possible states of the environment, and the other is the set Y of all possible information signals. An information signal y is a partition of the environment X. The information structure η is the partitioning of X into different signals of y. Therefore, a signal y will correspond to each x in X. An information structure is thus defined as y = η (x). Any partition of X can be viewed as a way to describe the states of the environment. As an example, suppose a marketing manager can offer a customer a product in small, medium, or large. The customer wants either small or medium. The marketing manager must make a decision about which size to choose, which will impact the design of the product, and the information relevant to his decision is the size small or medium. The set X of all possible sizes is thus partitioned into one subset, small, and another subset, medium, and this partitioning defines the information structure, η.

4.3 Expected payoff

The expected payoff method is based on the premise that every individual has preferences as to how to prioritize a list of alternatives due to personal beliefs or interests (assuming that the individual is consistent). Preferences can be described by the ranking of alternatives

according to some subjective probability distribution, consistent with what the person believes will happen. Under uncertainty, each of the alternatives is an action which may result in one or more outcomes, as discussed.

In this sense, the term 'utility' refers to the usefulness an action brings to an individual. For the order of preference given to all actions, each position can be assigned a single number representing the utility of each, or a person's desirability of the occurrence of an event, thus capturing his preferences. The probability of each action occurring is represented by the subjective probability assignments. The expected utility of an action is therefore the sum of the utilities of its various possible outcomes, weighted by the probability of each outcome's occurrence.

Given these basic definitions described in the previous section, for a set R of alternative outcomes r1... rN, if $Z_i(a)$ denotes the event that an action a results in the outcome r_i (since $r_i = \rho(x, a)$), then the "expected utility" Ω for an action a is:

$$\Omega(a; \rho, \pi, \upsilon) = \Sigma \upsilon(r_i) \pi[Z_i(a)] \tag{1}$$

where:

π = subjective probability function
υ = utility function.

The left-hand side of the expected utility function in (1) shows that the expected utility depends only on the decision-maker's action, given the functions ρ, π, and υ, which describe the factors which are out of his control. The individual's actions are under his control, and his goal is to choose the action which maximizes the corresponding expected utility. In the utility function $\upsilon(r)$ in (1), r can be replaced to obtain the new payoff function ω: $\upsilon(r) = \upsilon[\rho(x, a)] \equiv \omega(x, a)$. The expression in (1) can be further simplified by stating that, given the set X of alternative states of the environment x, the probability of the state x can be written as $\Phi(x) = \pi(\{x\})$, where Φ is the probability density (or mass) function, and x is assumed to be a random variable that is normally distributed. This expression is, in other words, the probability of the set X consisting of the single element x denoted by $\{x\}$. The expected utility function in (1) can be re-written as:

$$\Omega(a; \omega, \Phi) \equiv E \omega(x, a) = \Sigma \omega(x, a) \Phi(x) \tag{2}$$

The expression in (2) can now be called the expected payoff of the action a, where the expected utility depends on the decision-maker's action only, and where ω and Φ describe the factors uncontrolled by the decision-maker. Though the utility and the probability functions may be thought of as being controllable, it is assumed for simplicity that they are not, and that they are treated as givens of the problem. By replacing the actions by decision rules, and introducing the information structure into the equation, the payoff function can be re-written as:

$$\omega(x, a) = \omega[x, \alpha(y)] = \omega[(x, \alpha(\eta(x))] \tag{3}$$

From this, the expected payoff becomes:

$$U = \Sigma \omega[(x, \alpha(\eta(x))] \Phi(x) \equiv \Omega(\eta, \alpha; \omega, \Phi) \tag{4}$$

The expected payoff now depends on the decision function α and the information structure η, and on the factors over which the decision-maker has no control, namely ω, and Φ. The information structure η is assumed to be under the control of the team member; each member has the ability to observe and partition the information into the subsets needed for his activity. The individual has more than one pair (η, α) available, and he will choose the one that maximizes U. This expression is the measure that describes the performance of the various processes through the evaluation of actions under uncertainty. It is used to evaluate the process network diagrams to be developed in upcoming sections. The optimal process structure will be that which maximizes the expected payoff of the network under certain conditions, given the probability distribution of the states of the environment.

4.3.1 Expected payoff as a quadratic function

The payoff function can be expressed as a quadratic function of the team action variables. Although this is an approximation, it is useful. The quadratic function is one that has been used to describe many real-life phenomena, such as in economics for the law of diminishing returns. The concave quadratic function describes the expected payoff function in that there is a point that is optimum, i.e., the maximum point, and before and after this point, the value of the payoff decreases. The use of functions of orders higher than two is very complex and difficult to solve, and a linear function is neither sufficient nor appropriate to describe the present phenomena in detail since it is not expected that the payoff function continuously increases or decreases. Also, since the goal here is to make comparisons between two process structures, the relative comparisons do not require the payoff function to be exact. Taking the case of two members in a team, 1 and 2, where each must make a decision, then the quadratic payoff function can be chosen as:

$$u = -a_1^2 - a_2^2 + 2Q\, a_1 a_2 - 2\eta_1 (x)\, a_1 - 2\eta_2 (x)\, a_2 \qquad (5)$$

(the use of functions of x will be suppressed for simplicity in the future).

This particular form of the quadratic function is similar to the one used by Marschak and Radner (1972), with some of the coefficients chosen to simplify calculations. In the above expression, Q measures the interaction between a_1 and a_2, the action variables of team members 1 and 2, respectively, and must be between zero and one. The interaction is one of the micro-variables of the process model. For M action variables, if the second derivative of the expected payoff function exists, then a measure of the interaction between the action variables i and j is $\partial^2 \omega / \partial a_i \partial a_j$. In other words, it measures "the degree to which a change in action j influences the effect of a change in action i on the payoff for given values of the other action variables and of x" (Marschak and Radner, 1972, p.101). The functions $\eta_1 (x)$ and $\eta_2 (x)$ are related to the information structure.

The assumption that the payoff is quadratic gives meaning to the variances and the correlations of the information variables. Normal distributions are fully described by their means and variances. The variance can help gauge uncertainty, as it takes the difference between the maximum and minimum values of x. For multivariate distributions, the correlation coefficient describes the degree of statistical interdependence between variables (above, r describes the correlation between two variables). Due to the interdependencies in processes, it is often important to understand how one variable affects another. Whether this

is the correlation between action variables or the environment variables, it is reasonable that these correlations may affect the information structure and/or probability of occurrence chosen by the organizer. Another simplification is the normalizing assumption, where each variable is considered to be measured from its mean, so that $m = 0$, and $E(m) = 0$. There is no loss of meaning since this is simply a coordinate transformation. In this case, the correlation coefficient becomes:

$$r = r12 = Ex1x2/s1s2, \text{ or}$$

$$Ex1x2 = r * s1s2.$$

These properties of probability distributions will be useful in solving the expected payoff functions and determining the macro-variables of interest, discussed in upcoming sections.

4.3.2 Multi-person teams

For n members in a team, then there will also be n information structures and n decision rules. Each member i chooses an action ai from set Ai of all possible alternatives. The payoff function can be written as:

$$u = \omega (x, a1, a2 ...)$$

where u is now the utility to the team (and to each of its members). Although ai is the action variable controlled by the ith member, ai itself can be an m-tuple of many distinct variables, each controlled by the ith member. If there is no interaction among the action variables, then the payoff is said to be additive, and the form of the expression becomes:

$$\omega (x, a) = \Sigma \, \omega \, i \, (x, ai)$$

If, however, there are interactions among action variables, then the quadratic function must include an extra term to express this interaction, namely Q, as before.

4.3.3 Team decision functions and information functions

In a single person team, the person's action is related to the decision function through $a = \alpha(y)$. For a multi-person team, there are now n decision functions, $\alpha = (\alpha1 \ldots \alpha n)$ and ai = α1(yi). The same decision rules as before can be applied for a team. The joint action of the team members is $a = (a1, \ldots an)$, and $y = (y1, \ldots yn)$ is the team information, so there are n decision functions, and the team decision rule can then be denoted as $\alpha = (\alpha1, \alpha2, \ldots \alpha n)$. The same expression for an action $a = \alpha(y)$ for a single person team is also applicable for teams, keeping in mind what each term means individually. The information structure for each team member can be expressed as $yi = \eta i (x)$, and for the team, the information structure is $\eta = (\eta1, \ldots \eta n)$. Then, for $y = \eta (x)$, and $a = \alpha (y)$, $a = \alpha [\eta (x)]$ applies for the team action. The payoff of the team can be written, as before:

$$u = \omega (x, a1, a2, \ldots) = \omega (x, \alpha 1 [\eta1 (x)], \ldots \alpha n [\eta n (x)]) = \omega (x, \alpha [\eta (x)],$$

and the expected payoff of the team is:

$$E (u) = \Omega (\eta, \alpha) = E (\omega (x, \alpha [\eta (x)]) \tag{6}$$

4.3.4 Consideration of time

All the discussion up until now has involved the static case of the team decision problem, but time can be incorporated into the various concepts. If one team member's action at time t (t = 1,...T) is ai(t), and x(t) is the state of the world at time t, then the team action variable becomes:

$$a = [a1(1),…an(1),...an(T)],$$

and the state of the world is:

$$x = [x(1),...x(T)].$$

For yi (t) = ηi (x, t), the action variable becomes:

$$ai(t)= ai[ηi (x,t),t].$$

An important assumption of this situation is that for actions that are spaced apart in time, the larger the time difference, the less the interaction between those actions. Therefore, it is assumed for simplicity that the actions that are distant in time need less coordination than those that are closer together. The payoff function with no interaction is thus additive in time, and can be expressed as:

$$ω (x, a) = Σ ωt [x, a (t)] (for t=1,…T).$$

4.4 Design of network models

Networks can be used as a powerful tool to represent and evaluate the structure of a process, and more specifically, the structure of information flow and work patterns in a team. A network can be defined as a system of interconnected elements, all of which work together to produce a desired output. A network consists of the following basic components:

-   element (represented by a circle): the component which has the function of transformation of information. An element can represent a human being, a machine, a communication tool, etc., in the process of performing an activity.
-   input(s) (represented by an arc into the element): required for each element. These inputs are various types of information (e.g. information or actions coming from the previous element's output, noise from the environment, team members' personal knowledge or expertise, etc.).
-   output(s) (denoted by an arc leaving the element): the result of each element. This can be in the form of 1) processed information, 2) a simple relay or distribution of information, or 3) an action being sent out as a result of the transformation process, either to another element or to the environment.

Each element in a network has an input which is transformed into or transferred as an output; the message of this output then feeds into one or more downstream elements. Elements are connected to one another through the input and output arcs, which carry information messages to and from elements. Messages coming from the environment (i.e., external to the organization) are called observations. Messages from one element to another

are communication, while messages going out into the environment are called actions. In the context of an organization, networks can be used to represent processes from an information processing point of view. Once all intermediate elements have been completed, a final action(s) is issued, which signals project completion. Networks can be organized according to time structure.

4.4.1 Connections between elements

The connections between elements in a network can be described in the form of a square array. For each element i and j, the set of all possible messages that can be sent from i to j, is denoted by B_{ij}. Any messages that come from outside, that is, from the environment, are described by the set Z_i, and E_i which denotes the set of all possible values of noise coming from the environment to element i. This noise can be information that is observed from outside the organization, such as customer input, best practices, etc. The messages sent out to the environment are defined as the action variables, $a = (a_1, \ldots a_n)$, for n actions, where a is the team action variable.

The set B_{i0} denotes the set of all possible messages from element i to the environment. This set will consist either of the Cartesian product of some sets A_j, where for each j, A_j is the set of all possible values that action variable a_j can take, or it will be empty since not all elements will have an action as an output. The set B_{0i} is symmetric to this set, and it represents the set of all possible messages from the environment outside to an element i, which is the Cartesian product of Z_i and E_i. Therefore, the set B_i of possible alternative output messages of element i is denoted by $B_i = \Pi B_{ij}$ (j=0...m). For m elements, the set $\acute{B}_i$ of combined messages from other elements to i is given by $\acute{B}_i = \Pi B_{ki}$ (k=0...m). The transformation of each element i is expressed through the task function $\beta_i = (\beta_{i0}, \ldots, \beta_{im})$, which transforms each input message into an output message. The set B_{ii} is empty as it is assumed that messages will not be sent from an element to itself. Figure 5 below shows an example of a simple network diagram. The corresponding square array consisting of the sets B_{ij} in Table 1 illustrates message transfers between elements in the figure. The symbol Φ denotes an empty set.
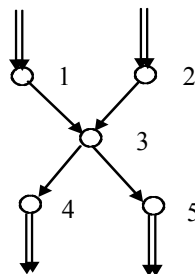

Fig. 5. Simple network diagram.

	0	1	2	3	4	5
0		B01	B02			
1				B13		
2				B23		
3					B34	B35
4	B40					
5	B50					

Table 1. Information dependencies.

The time distribution and spatial distribution of members in a team must be separated. For teams in a dynamic environment, networks are divided into time periods by several elements based on the structure of information flow, which is illustrated by elements broken down into intermediate stages or actions. Figures 6 and 7 show the network diagrams of possible sequential and CE processes.
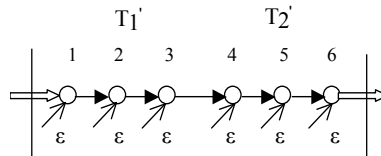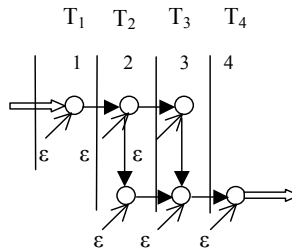

Fig. 6. Sequential network diagram.

Fig. 7. CE network diagram.

In the context of NPD processes, as an example, an element i can be a designer who receives information ε from the environment, say from the customer. An action a can be the release of design specifications from the designer to another element, say the manufacturing resource. This resource then uses information from this action as well as information from observations through personal experience and/or company databases for example, transforms the new combined information, and takes an action, such as manufacturing the product. This action is sent out to the environment, i.e., the customer.

4.5 Application to models

A simple model is designed in this section using network diagrams and its evaluation using the expected payoff method will be studied. The main purpose here is to compare the

relative differences between process structures in terms of the expected payoff. In the evaluation that follows, the expected payoff function is equation (5), repeated here:

$$u = -a_1^2 - a_2^2 + 2Q\, a_1\, a_2 - 2\eta_1\, a_1 - 2\eta_2\, a_2 \tag{5}$$

Recall that the coefficient "Q" in (5) denotes the interaction, specifically in this case between two overlapping activities occurring in the same time period. This function evaluates every step of performing work, and also evaluates the different processes as a whole (i.e., each intermediate step is evaluated using this function, as well as the overall structure of the network).

4.5.1 Assumptions of the model

In order to compare the two processes at the same level, some assumptions must be made to ensure consistency. First, both of the processes begin with the same input information variable η_i which is a random variable dependent upon x. Thus, the first member of each process begins by observing the same information that is coming from the environment. Another assumption in the model is that the members inside the organization not only receive information from other sources (i.e., other elements or the environment), they also contribute to the processing of their work through the use of their own expertise, which is denoted in the models by ε as an input into each element (Howard, 1966). However, this is considered as being a special state of the set X of information from the environment despite the fact that it comes from the element itself. Therefore, during the evolution of the activity, not only does the information that a member receives get processed, but also because each member is contributing his own knowledge and expertise, this pooled information adds value to the activity, which results in an increase in the expected payoff.

Earlier, it was mentioned that the choice of the payoff function as a quadratic equation is appropriate since a quadratic function has a maximum point. This assumption is important and must be re-stated. Furthermore, since the expected payoff is the measure being used to compare relative process performance, an absolute measure is unnecessary, so the problem of defining a specific and accurate form of the function can be avoided.

The cost of a network is not considered in the models. Marschak and Radner (1972) did not include this important factor explicitly in their decision functions, although they acknowledge its importance. There is a cost associated with decision-making, with how information is obtained, with team organization, etc. In the context of this research, cost was not chosen as a parameter of the models, however, since cost can help in assessing the trade-offs of one process design over another.

The sequential and CE process networks are created as sequences of single-period decision problems (see Figures 9 and 10), where the interaction between periods is assumed to be zero, i.e., Q=0, as previously discussed in Section 4.4.4. Thus, interaction is assumed to be zero across periods, though there is interaction within time periods. Therefore, it is assumed that the total payoff function is additive in time. In each time period, optimal decisions are made. This difference in interactions addresses the case for which the sum of the maximum expected payoffs is equal to maximum of the sum of expected payoffs. In other words:

$$\text{Max } \Sigma\, E\, \omega\, (x, a) = \Sigma\, \text{Max } E\, \omega\, (x, a) = \Sigma\, E\, \omega\, \text{max}\, (x, a).$$

Thus the maximum expected payoff is calculated in each period, which are the added up to give the total maximum expected payoff. In other words, the expected value of the maximum payoffs is equal to the total maximum expected payoffs for each period.

Rework is not modeled in either the sequential or CE process. Though this is a simplifying assumption not characteristic of most NPD processes, the model is presented in basic form, with the intent of bringing out some essential features of the expected payoff method.

The simple network shown below in Figure 8 will be defined here to illustrate how a network diagram is evaluated in terms of its gross expected payoff ('gross' since the cost of a network is not considered). The network is assumed to be in one time period, reflecting a single action. In cases when there is more than one element, each element in the network can be evaluated separately in terms of its expected payoff, and the total expected payoff is simply the sum of the individual ones. Actions taken at different times can be considered to be corresponding to different team members.
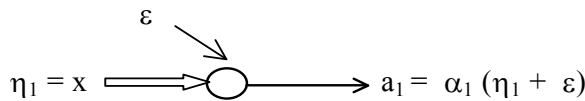
$$\eta_1 = x \implies \bigcirc \longrightarrow a_1 = \alpha_1 (\eta_1 + \varepsilon)$$

Fig. 8. Action taken in one time period.

Figure 8 illustrates an action. Element 1 has $\eta_1 = x$ as input variable, where η_1 is a random variable dependent upon the state of nature x (which is suppressed). The state variable observed by the team member at element 1 is processed, which also receives some information ε from outside (qualified as information such as team member's personal expertise), which, for simplicity, is considered to be a constant. This information is processed, and an action a_1 is taken, which is a function of the inputs to the element. The information ε combined with the information μ_1 is additive. With a single action, the payoff function is chosen as a quadratic in one input variable, in the form:

$$\omega = -a_1^2 + 2a_1x \tag{6}$$

Taking the derivative of (6) with respect to a_1 and setting it equal to zero gives:

$\omega' (a_1) = -2a_1 + 2x = 0$, and solving for a_1 gives the best decision function, denoted by $\dot{\alpha}$:

$$\dot{\alpha} (x) = x \tag{7}$$

which is the optimal decision. The second derivative of (6) is negative (-2), ensuring a maximum point, so plugging (7) back into (6) and taking the expected value of the payoff gives the following expected value of the maximum payoff:

$$\Omega = E (x + \varepsilon)^2 = s^2 \tag{8}$$

where s^2 is the variance of x. The decision function in equation (7) has a distribution of possible decisions, which implies that multiple choices can be made. Assuming that this distribution is normal, then, equation (8) shows that the payoff is equal to the variance. This

means that in making a decision, i.e., reducing possible choices to a single value, the payoff is equal to the value of the reduction of uncertainty of information. It is reasonable to conclude that the larger the variance, i.e., the more uncertain the decision, then, the more benefit (payoff) there is in making a decision.

4.5.2 Sequential engineering network diagram

The sequential engineering network diagram is illustrated in Figure 9, and consists of six time periods, T1 to T6, which represent the division of the sequential work done by six different functional team members. Team member 1 receives complete information represented by the state variable x, and then uses this information, along with his own expertise represented by ε, to complete his activity. At the end of his activity, he sends complete information to the downstream activity, which is again processed by the second team member. The output of this activity is a message sent to the next team member, etc.
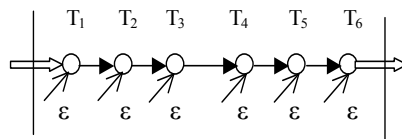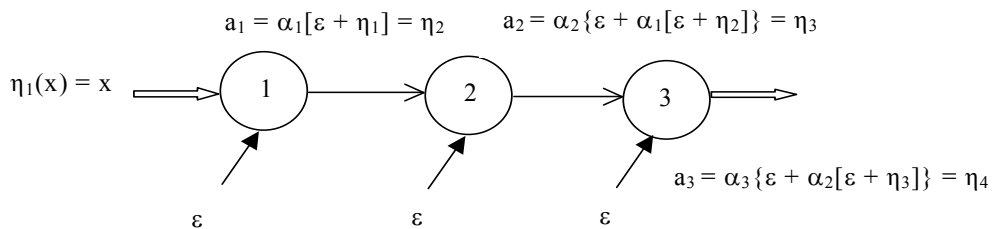

Fig. 9. Sequential network diagram.

Because of the assumption of no cross-functional communication in a sequential process, there is no interaction between team members, and the communication of information is assumed to be 'over-the-wall', thus even if there is some interaction, it is assumed to be so weak that it is negligible.

Evaluation of the Network

1.   First Period T1:

$$a_1 = \alpha_1[\varepsilon + \eta_1] = \eta_2 \qquad a_2 = \alpha_2\{\varepsilon + \alpha_1[\varepsilon + \eta_2]\} = \eta_3$$

$$\eta_1(x) = x$$

$$a_3 = \alpha_3\{\varepsilon + \alpha_2[\varepsilon + \eta_3]\} = \eta_4$$

Similar to the example above, team member 1 receives complete information, and every member within the network contributes his special technical knowledge to the flow, denoted by ε. As before, the payoff function is (6) and the expected payoff is (9):

$$\omega = -a1^2 + 2a1x \qquad (6)$$

$$\Omega_1 = s0^2 \qquad (9)$$

where s02 = E(x + ε) 2.

2.   Second Period T2:

As in time period 1, member 2 receives output x from element 1, giving the payoff:

$$\Omega\, 2 = s12 \tag{10}$$

where s12 = E(x + ε + ε) 2.

A similar procedure as above applies to each time period, up until time period six. The total Expected Value of the Maximum Payoff:

$$\Omega = \Sigma\, (i = 1\ldots 6)\, \Omega\, i = \Omega\, 1 + \Omega\, 2 + \Omega\, 3 + \Omega\, 4 + \Omega\, 5 + \Omega\, 6$$

$$= s02 + s12 + s22 + s32 + s42 + s52$$

If it is assumed for simplicity that the variance for each information structure is the same, then the total expected payoff becomes:

$$\Omega\, TOT = s02 + s12 + s22 + s32 + s42 + s52 = 6s2 \tag{11}$$

4.5.3 Concurrent engineering network diagram

The concurrent engineering diagram shown in Figure 10 is an appropriate modification of the sequential engineering network. It takes into account the two teams of three members each, but this time with a few added features. The two teams' activities are now overlapping in time periods T2 and T3. These two teams now are also communicating with each other through the transfer of information denoted by the arrows between overlapped activities. There is interaction between the two members from both teams in the same two time periods. Since rework is not modeled, overlapping part of the six time periods in the sequential process gives the resulting four time periods in the CE process. The main comparison of interest at this point is the difference between expected payoffs.
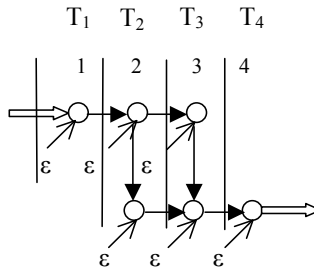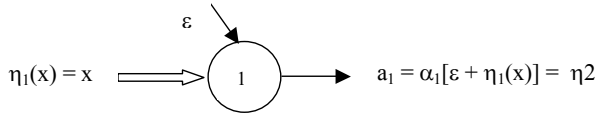

Fig. 10. CE network diagram.

Evaluation of the Network

1.   First Period T1:

Again, it is assumed that member 1 obtains complete information x, that is the information structure $\eta_1(x)=x$. Also, every member within the network contributes his special technical knowledge to the processing and transferring of information. The output $\alpha[x] = a_1$ is determined as before. Choosing $u_1 = \omega (x, a_1) = -2a_1^2 + 2a_1[x + \varepsilon]$, the best decision function is:
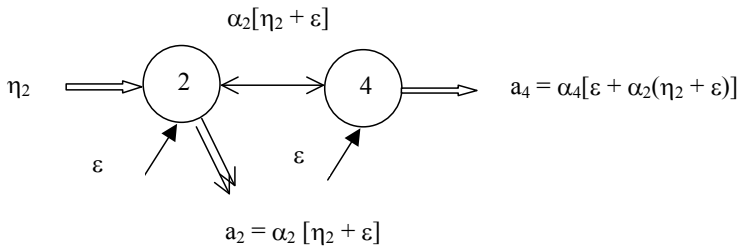
$$\dot{\alpha}\,[x] = x + \varepsilon$$

and the expected value of the maximum payoff for the first time period is:

$$\Omega\,1 = s\,0^2 \tag{12}$$

where $s0^2 = E[x + \varepsilon]$

2.   Second Period T2:

The payoff function is:

$$\omega(x, a) = -a_2^2 - a_4^2 + 2Q\,a_2\,a_4 - 2\,\eta\,2\,a_2 - 2\,\eta_4\,a_4 \tag{13}$$

Taking the first derivative of the payoff function first with respect to a2 and a4 setting each equal to zero:

$$\delta\omega/\delta a_2 = -2a_2 + 2Q\,a_4 - 2\,\eta\,2 = 0 \tag{14}$$

$$\delta\omega/\delta a_4 = -2a_4 + 2Q\,a_2 - 2\,\eta\,4 = 0 \tag{15}$$

gives the following system of equations:

$$- a_2 + Q\,a_4 = \eta\,2 \tag{16}$$

$$Q\,a2 - a4 = \eta\,4 \tag{17}$$

Solving for a2 and a4 yields the following best decision functions for T2 period actions:

$$\dot{\alpha}2 = [-1/(1-Q2)] * \eta\,2 + [-Q/(1-Q2)] * \eta\,4$$
$$= [-1/(1-Q2)] * [x + \varepsilon + \varepsilon] + [-Q/(1-Q2)] * [x + \varepsilon + \varepsilon + \varepsilon] \tag{18}$$

$$\dot{\alpha}4 = [-Q/(1-Q2)] * \mu\,2 + [-1/(1-Q2)] * \eta\,4$$
$$= [-Q/(1-Q2)] * [x + \varepsilon + \varepsilon] + [-1/(1-Q2)] * [x + \varepsilon + \varepsilon + \varepsilon] \tag{19}$$

Plugging (18) and (19) into (13) gives the payoff for time period T2:

$$\omega = [\eta\,22 + 2Q\,\eta\,2\,\eta\,4 + \eta\,42]/\,[1-Q2], \tag{20}$$

and the expected payoff is:

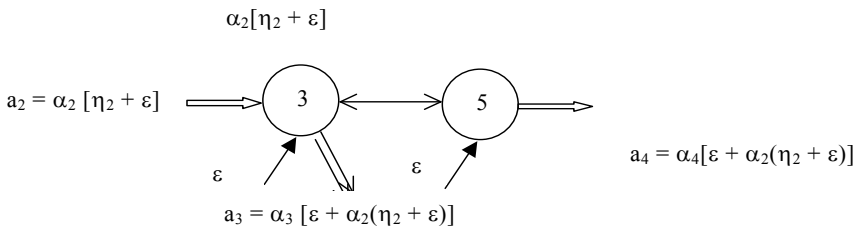$$\Omega\,2 = E\omega = [s12 + 2Qr12\,s1\,s2 + s22]/\,[1-Q2] \tag{21}$$

where:

$$s12 = E\,[x + \varepsilon + \varepsilon]\,2$$

$$s22 = E\,[x + \varepsilon + \varepsilon + \varepsilon]2$$

$$r12 = [E\,(x + \varepsilon + \varepsilon)(x + \varepsilon + \varepsilon + \varepsilon)]/\,s1\,s2$$

where r12 is the correlation coefficient and Q is the interaction.

3.　　Third Period T3:

The payoff function is:

$$\omega = -a32 - a52 + 2Q\,a3\,a5 - 2\,\eta\,3\,a3 - 2\,\eta\,5\,a5 \tag{22}$$

where:

$$\eta\,3 = \varepsilon + \dot{\alpha}\,2 = [-1/(1-Q2)] * [x + \varepsilon + \varepsilon] + [-Q/(1-Q2)] * [x + \varepsilon + \varepsilon + \varepsilon] + \varepsilon \tag{23}$$

$$\eta\,5 = \varepsilon + \dot{\alpha}\,2 = [-Q/(1-Q2)] * [x + \varepsilon + \varepsilon] + [-1/(1-Q2)] * [x + \varepsilon + \varepsilon + \varepsilon] + \varepsilon \tag{24}$$

Performing the same calculations as in T2 gives the following best decision functions:

$$\dot{\alpha}3 = [-1/(1-Q2)] * \eta\,3 + [-Q/(1-Q2)] * \eta\,5$$

$$= [-1/(1-Q2)] \{-1/(1-Q2)] * [x + \varepsilon + \varepsilon] + [-Q/(1-Q2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon\} + \tag{25}$$

$$[-Q/(1-Q2)] \{-Q/(1-Q2)] * [x + \varepsilon + \varepsilon] + [-1/(1-Q2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon\}$$

$$\dot{\alpha}5 = [-Q/(1-Q2)] * \eta\,3 + [-1/(1-Q2)] * \eta\,5$$

$$= [-Q/(1-Q2)] \{-1/(1-Q2)] [x + \varepsilon + \varepsilon] + [-Q/(1-Q2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon \} + \tag{26}$$

$$[-1/(1-Q2)] \{-Q/(1-Q2)] [x + \varepsilon + \varepsilon] + [-1/(1-Q2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon \}$$

The expected payoff is:

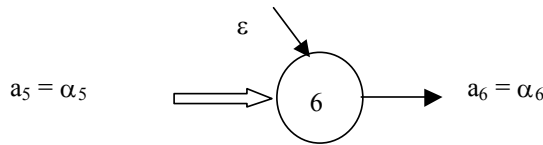$$\Omega\,3 = [s32 + 2Qr34s3\ s4 + s42]/\ [1-Q2] \tag{27}$$

where:

$$s32 = E[-1/(1-Q2)\ [x + \varepsilon + \varepsilon] + [-Q/(1-Q2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon]2$$

$$s42 = E[-Q/(1-Q2)\ [x + \varepsilon + \varepsilon] + [-1/(1-Q2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon]2$$

$$r34 = E[\eta 3\ \eta\ 5]/\ s3\ s4$$

4.   Fourth Period T4:

The payoff function is chosen as:

$$\omega = -a62 + 2a6\ \eta\ 6 \tag{28}$$

where:

$$\eta\ 6 = \varepsilon + \dot{\alpha}\ 5$$

$$= (-Q/(1-Q2) \{[-1/(1-Q2)]\ [x + \varepsilon + \varepsilon] + [-Q/(1-Q2)]\ (x + \varepsilon + \varepsilon + \varepsilon + \varepsilon) + \varepsilon] + \varepsilon$$
$$+ (-1/(1-Q2)\ \{[-Q/(1-Q2)]\ [x + \varepsilon + \varepsilon] + [-1/(1-Q2)]\ (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon] + \varepsilon\} \tag{29}$$

The best decision function is:

$$\dot{\alpha}\ 6 = \eta\ 6 \tag{30}$$

Therefore the expected value of the maximum payoff is:

$$\Omega\, 4 = s52 \tag{31}$$

where:

$$s52 = E\, [\varepsilon + \dot{\alpha}\, 5]2$$

Total Expected Value of the Maximum Payoff:

$$\Omega = \Sigma\, (i = 1...4)\, \Omega\, i = \Omega\, 1 + \Omega\, 2 + \Omega\, 3 + \Omega\, 4$$

$$= s02 + [s12 + 2Qr\, s1\, s2 + s22] / [1\text{-}Q2] + [s32 + 2Qr34s3\, s4 + s42] / [1\text{-}Q2] + s52 \tag{32}$$

$$= [s02 + s52] + [s12 + s22 + s32 + s42] / [1\text{-}Q2] + [2Q(r12\, s1\, s2 + r34s3\, s4) / [1\text{-}Q2]$$

$$\Omega\, TOT = A + B/[1\text{-}Q2] + CQ/[1\text{-}Q2]$$

where the coefficients A, B, C are:

$$A = s02 + s52$$

$$B = s12 + s22 + s32 + s42$$

$$C = 2(r12s1\, s2 + r34s3\, s4)$$

5. Results

From the calculations in the previous section, the total expected payoffs are summarized below for each of the two processes:

Sequential: $\qquad \Omega\, TOT = s02 + s12 + s22 + s32 + s42 + s52 \tag{11}$

CE: $\qquad \Omega\, TOT = A + B/[1\text{-}Q2] + CQ/[1\text{-}Q2] \tag{32}$

where the coefficients A, B, and C are as before. The equation for the expected value of the maximum payoff for the sequential process is a constant with respect to Q, while for the CE process it is polynomial in Q. If it is assumed for simplicity that all variances are equal and the correlation coefficients are equal to zero, i.e., the information variables are independent, then Figure 11 depicts the resulting curves for each process.
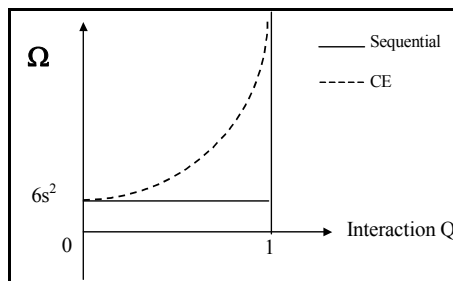

Fig. 11. Expected payoff vs interaction.

This analysis shows that a CE process is always better than a sequential one in terms of expected value of the maximum payoff. This is contradictory to practical observations of both processes. This is due to the fact that the analytical model oversimplifies the sequential process, whereby it is assumed that there is virtually no interaction between phases, and that information is 'thrown over the wall' from one function to another. Under this assumption, there is no interaction, which naturally results in an expected payoff that is independent of the interaction, Q, thus giving a constant. Additionally, it is also assumed in the modeling process that the contribution of each member's specialized information is the same for both the sequential and CE processes. This results in the total expected payoff for the sequential process being always lower than that of CE. Again, this assumption is not consistent with practical observations. In order to make the analysis more meaningful, some further assumptions should be made with regards to team members in a sequential process as compared to a CE process.

In some practical situations, a sequential process can be better than a CE process (Krishnan et al., 1997). When this is true, in the modeling process it is reasonable to assume that for a sequential process, every team member's knowledge and information is sufficient to allow him to finish his activity independently. In fact, it may even be argued that in a sequential process, the amount and types of information that functional members must possess is greater than members in a cross-functional team, which allows them to finish their activity independently. They must possess not only information about their own specialization, but they must also have, to some extent, information about other functions as well. After all, a designer will not design a product which requires milling if the company does not own a milling machine. In contrast, in a CE process, it can be assumed that members on a cross-functional team do not need to possess as much information about other functions since sharing of information will occur naturally as a consequence of teamwork, in which case it is reasonable to assume that more work is required to obtain information. Therefore, the variance of knowledge and information measured by s^2 is assumed to be larger for members in a sequential process than for the same members who would work in the overlapped periods in a CE process. This implies that the lack of information or knowledge by members in a CE process can be compensated by the exchange of information in the overlapped periods.

Given this assumption, the straight line in Figure 11 would move up the y-axis, while the CE curve would remain the same. This would create a point of intersection between the two curves, indicating that, for a given point of interaction, one process will be superior to the other in terms of expected payoff. For simplicity, it is assumed that for the CE process, all variances are equal to 1, and that the correlation coefficients are equal to 0. It can be further assumed that team members 2, 3, 4, and 5 in a sequential process have a variance that is slightly higher than the same members in a CE process, who, as explained above, exchange information during the overlapped periods. For simplicity, the variance for the sequential members' information is taken to be one-quarter higher than that of the CE members' information i.e., s_i^2 (sequential) = 1.25 s_i^2 (CE). Plugging these values back into 11 and 32, the total expected payoffs are:

Sequential: Ω TOT = 8.25

CE: Ω TOT = 2 + 4/[1-Q2]

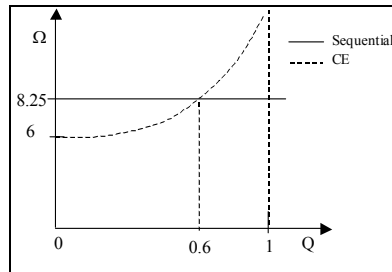This analysis is now illustrated in Figure 12.

Fig. 12. Expected payoff vs interaction.

The curve for the CE process shows how the expected value of the maximum payoff changes with interaction, showing that as team interaction increases, the expected payoff increases as well. For this particular case, it was found that a sequential process has a higher expected payoff when the interaction is lower than 0.6, and a CE process has a higher payoff for values of interaction greater than 0.6. In other words, the results show that when actions in a CE process highly influence one another, i.e., the interaction is higher than 0.6, then a CE process is more valuable in terms of expected value of the maximum payoff. If the interaction between action variables is not strong, i.e., less than 0.6, then the sequential process is sufficient, and superior in terms of expected payoff.

In conclusion, the expected payoff method from decision theory provided some initial results in the comparison of a sequential and CE process. From the mathematical derivation presented in this chapter, comparing equation (11) to (32) shows that a CE process is always more valuable than a sequential process in terms of expected payoff. In most instances in reality, however, a sequential process has some benefit. Under the conditions when this holds true, the sequential process has a higher total expected payoff when the interaction intensity is low, while CE is better than a sequential process for high interaction.

6. Conclusion

The expected payoff method is presented here as a very simple introduction to studying NPD processes. A more elaborate and detailed development is in progress (Kong and Thomson, 2001), the results of which are expected to provide a major contribution to the existing body of work in studying organizational processes and their coordination.

Some avenues for future research are now discussed. In the comparison of sequential and CE processes, it is assumed that there is no interaction between team members in the sequential process, thus emulating the 'over-the-wall' approach, where team members throw information over an invisible wall. In practice however, there exist interactions among members (or departments) of a team, though they may be very weak. Future work should consider this. It was stated that the expected payoff method assumes that individuals in a team work towards achieving common goals with common interests and beliefs within

the constraints of their work, all of which guide their behavior. For a CE team, this is conceivable in the sense that any 'team' usually works together to achieve some goal, and a cross-functional team, ideally, works towards the common project goals of being on time, and within budget. However, in practice there is tension between meeting project and functional goals, as team members have project-specific goals, but also have departmental obligations to fulfill. The same assumption is debatable for a sequential process, where functional teams in different activities tend to have differing goals. For example, in isolation, a designer's goal is to create a product design without much concern for the production process that will build it. Similarly, a marketing manager's goal is to get customers to buy the company product without much concern for how the product will be made. This is partly due to the fact that functional goals are tied to functional rewards. Taking into account this divergence of beliefs would require further analysis into economic and organization theory where individuals' actions are based on self-interest. A more detailed description of the influence of time on the payoff function must be developed. Presently, it is assumed that interaction between action variables at different times is weaker the farther apart they are in time. However, if there is interaction between actions at different times, the payoff function will not be additive in time. The sequential process will have constraints which link actions that are distant in time, and can no longer be evaluated as a series of single-period problems, in which interaction is so weak that it does not exist. Most activities are not deterministic in a product development process. In fact, many situations arise where a stochastic relation between activities apply. A commonly occurring phenomenon is the failure of one or more activities, which consequently require rework. Rework loops in the network diagrams must be expressed to incorporate this very important characteristic of development processes. The function of rework in a network is to prevent the expected payoff from reaching a maximum when an activity is reworked, though a maximum can be reached after a few iterations but at a greater cost. The measure of the expected utility of a network has always been considered in its gross form, that is, without any consideration for the cost of the network. In reality, obtaining information can be very costly, and though one network may be superior to another in terms of the expected payoff, the cost of that network may not justify its use. This concept should also be incorporated into the models.

7. Acknowledgment

8. References

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