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Strategic Management of Complexity in Distributed Product Development

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ABSTRACT

Global, dynamic, and competitive business environment has increased the complexity of managing product development (PD) processes. In distributed PD, complexity management means information simplification and management between the collaborating partners. In this article we present a literature review of PD complexity and its management. Furthermore, we propose decomposing PD complexity into four components: environmental, organizational, product and process complexity. Consequently, an aggregate measure of PD complexity is developed. Finally, we introduce a conceptual framework for complexity management in distributed PD environments.

(Keywords: Management of complexity, Collaborative and Distributed Product Development, Information Management, Knowledge Management, Information Technology, Structured Framework).

*“Seeing only individual actions and missing the structure underlying the actions...lies at the root of our powerlessness in complex situations.”
Peter M. Senge, The Fifth Discipline*

1. Introduction

Some of today’s phenomena are marvelously predictable, but some of the most unpredictable ones, like weather, are so convoluted, that they continue to elude the best forecasters. Scientists call them complex systems. Though made up of relatively simple units- like the molecules in the atmosphere- the pieces interact to yield behavior that is full of surprise. Philippe W. Anderson, who won the Nobel Prize in Physics in 1977, described complex systems by saying, ”More is different”. Whether cells interact to form an organism or organisms to form an ecosystem or gas molecule interact to form a weather front, the result is what people intuitively consider complex.

For all the effort to understand these phenomena, scientists are still puzzling over a very basic question: What is meant by complexity? How can the essence of complexity be captured and quantified in a precise definition? Complexity seems to be still a theoretical concept. In the absence of a good definition, “complexity is in the eye of beholder”. As an example, forecasting the behavior of the Internet with all its interacting pieces of possibilities could be enormously difficult. Current technology, hardware and software are rapidly approaching biological levels of complexity.

Increased competition and globalization of businesses are forcing manufacturing companies to develop new products faster. Electronic business, which brings customers, vendors, suppliers and employees together, is influencing the way we operate our companies through the use of information technology. Time-to-market has to be reduced, efficiency has to be increased, and companies are outsourcing more and more of their businesses, even Product Development (PD). This leads to a complex and distributed development process. Furthermore, complexity is increasing due to new generations of products with multiple functions in diverse operating conditions. The implementation of technologies is becoming more multidisciplinary and the use of external knowledge has increased rapidly. Systems interaction has become complex and subsystems share and exchange not only information, but also knowledge, methods, and tools with each other.

Complexity appears in PD companies in several forms. In this article, we characterize complexity under three topic areas: business, technology, people. All the areas of complexity are dependant on each other. Managing complexity requires the knowledge of each part and the interrelationship between them. Networking relates to all of the areas.

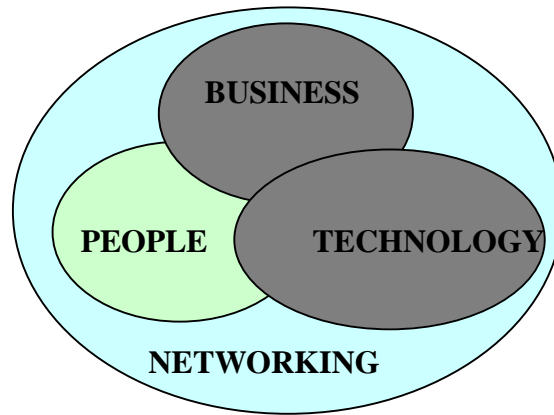


Figure 1 The interrelationship between complexity areas

The business environment forces companies to concentrate their efforts on excelling in one of the three areas: product innovation, customer relationship management or infrastructure management [Hagel & Singer, 1998]. You can basically be excellent only in one of them and outsource the others or build up virtual enterprises.

Business process organization, especially product development process organization is based on competence node networking [Salmelin, 1999]. Tasks are allocated to the competence node, which understands the customer problem best. The traditional value-chain based business is transformed to value networks where product development processes are running in inter-organizational environment. Somehow the trend seems to be towards dynamic markets in which internal and external service providers will execute the development activities. The management will be done according to value recognition and networking. Clusters of networked organizations are collaborating around a specific technology and make use of a common architecture to deliver independent elements of value that grows with the number of participating organizations.

The rest of the paper is organized as follows. Section 2 provides a definition of complexity compiled from different sources of the complexity literature. In Section 3, we introduce our definition of complexity and the concept of complexity decomposition. In Section 4 we propose a strategic management framework to reduce and manage complexity in distributed environments. In Section 5, we end the paper with a brief summary.

2. Definition of Complexity

A simple definition for complexity shows that it is a measure of the difficulty we have in understanding or working with something and it typically increases when the number of attributes or situations that exist simultaneously increases [Boppe, 1997]. Complexity sources are many and varied. There are no simple means for quantifying complexity:

- Considerable knowledge, study and effort are needed to analyze and understand it.
- Complexity is tightly linked to human perception and levels of tension or stress.
- Complexity is pretty much in the eye of the beholder.

There has been a lot of discussion and argument within the communities of mathematicians, scientists and engineers, what is the notation of complexity. The subject is still being debated, as it lacks a common definition of complexity, concrete theories that can predict complex phenomena and mathematical tools that can deal with problems involving complexity.

In axiomatic design, complexity is defined only when specific functional requirements or the exact nature of the query are defined, [Suh, 1999]. Suh has defined complexity as a measure of uncertainty in achieving a set of specific functions or functional requirements. Complexity is related to information, which is defined in terms of the probability of success of achieving the Functional Requirements. There are two classes of complexity:

- Time dependant complexity, which has two types of real complexity
 - Time dependant combinatorial complexity and
 - Time dependant periodic complexity
- Time- independent complexity, which has two orthogonal components
 - Real complexity and
 - Imaginary complexity.

The vector sum of them is called absolute complexity. Real complexity of coupled design is larger than that of uncoupled or decoupled designs. Imaginary complexity can be reduced when the design matrix is known. Time-independent complexity is dealing with complexity involved in making design decisions because of the uncertainties inherent in the system designed and the uncertainties caused by the lack of knowledge. Time-dependent uncertainty occurs because the future events occur in unpredictable way and thus cannot be predicted. Many of these problems are combinatorial problems that can grow complicated indefinitely as a function of time, because the future events depend upon the decisions made in the past but in an unpredictable way.

Khurana [Khurana, 1999] has categorized complexity in five areas:

- Logistical Complexity
 - Result of a high volume of transactions or tasks or product proliferation
- Technological Complexity
 - Inherent complexity of the system and its technologies (products and processes)
- Interaction complexity and no decomposability
- Organizational Complexity
 - Organization structure, forms and procedures
- Environmental Complexity
 - Results from characteristics or events outside the system or organization

Warfield has introduced the definition of Domain of Complexity [Warfield, 2000]. The assumptions that engineers typically make, which serve them in normal or ordinary engineering practice, are almost dysfunctional in the Domain of Complexity. It has been

recognized that there is no single type of model that is satisfactory in the light of the enormous demands that must be satisfied to achieve broad applicability. Engineers must pay much more attention to the broad needs for communications in a variety of forms. The use of modeling in a form that everybody can understand the common meaning is becoming more and more important.

Levitt et al [Levitt, et al, 1999] introduced the concept of activity complexity. It refers to how many variables must be considered simultaneously in one activity while solving a problem. To determine activity complexity they added the requirement complexity of each of the requirements to which the activity contributes. They argue that activity complexity increases as a linear function- not an exponential or factorial function- of requirement complexity.

Eppinger has used methodology created by Steward's [Steward, 1981] Design Structure Matrix (DSM) in reducing complexity on:

- Task level: by structuring tasks into sequential, parallel and coupled tasks and optimizing iteration cycles [Eppinger, 1991].
- Product and organization level: through design decomposition to show complex interactions between components of a design and through integration analysis by translating a given product decomposition into a product architecture and development team structure [Pimmler and Eppinger, 1994].

3. Complexity Composition

Complexity can be decomposed into two main parts: external complexity and internal complexity. External complexity consists of important uncertain elements surrounding the organization that are outside its control. We refer to these elements as the business environment. To understand PD complexity, we need to study the business environment. Internal complexity can be further decomposed into three parts where each part is directly influenced by (or derived from) organizational decisions made throughout the PD process. Elements of internal complexity are:

- Product/Service complexity
- Organizational complexity
- Product development process complexity

These pieces of complexity are overlapping and interrelated, which makes the overall complexity difficult to manage. Instead it is easier to concentrate on complexity reduction. Total complexity can be decomposed into smaller parts according to figure 2. Each of the four complexity areas is described below.

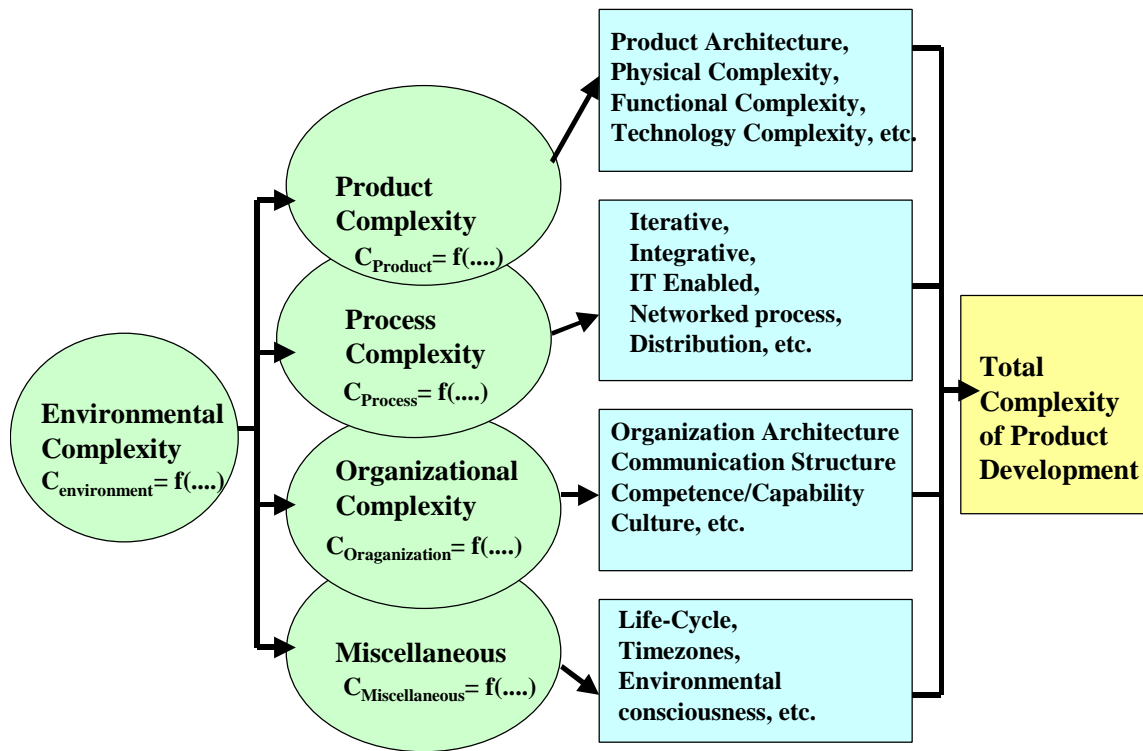


Figure 2. Decomposition of Total Complexity

3.1. Environmental Complexity

Enterprises do not operate in vacuum. They react to forces and changes surrounding them. Hence, the business environment plays a critical role in shaping the strategy of the whole enterprise. This environment is usually uncertain and has extremely nonlinear behavior. The more dynamic and uncertain this environment is, the more complex is the business strategy dealing with it.

Several environmental elements play a role in the composition of environmental complexity. These elements include innovation, technology, customer needs, competition, demand, economic conditions, and laws/directives, to name a few. As an example, a disruptive technology can change the whole business focus or the needed competence portfolio. This may lead to a set of innovations that influence the creation of a new product portfolio. Furthermore, increased intelligence (for example in automobile) can influence the birth of new service businesses. New environmental laws can completely prohibit the marketing of a product or a whole range of products.

In order to evaluate environmental complexity (C_e), managers could brainstorm and enumerate all the relevant environmental elements, then assign different weights to each in order to reflect its importance and impact on the organization.

3.2. Product Complexity

Customers are becoming extremely educated and demanding. Consequently, organizations are forced to design products able to deliver multiple functions under diverse operating conditions. This phenomenon resulted in an increased product complexity. Some companies resorted to “Modular designs” and “product platforms” to handle this increasing product complexity.

Modularity is a strategy for organizing complex products and processes efficiently. A modular system is composed of modules that are designed independently but still function as an integrated whole. Designers achieve modularity by portioning information into visible design rules and hidden design parameters [Baldwin and Clark, 1997]. Visible design rules fall into three categories: Architecture, Interfaces and Standards for testing a module’s conformity to the design rules. The hidden design parameters (hidden information) are decisions that do not affect the design beyond the local module. Hidden elements can be chosen late and changed often and do not have to be communicated to anyone beyond the module design team or individual.

A product family is defined as a set of products that share common technology and address a related set of market applications. An evolving product family will introduce new technologies into product designs and target new customer requirements. The technological foundation of the product family is defined as the product platform. A platform is the physical implementation of a technical design that serves as the base architecture for a series of derivative products. The commonality of technologies and markets leads to efficiency and effectiveness in manufacturing, distribution and service, where the form tailors each general resource or capability to the needs of specific market niches [Meyer and Utterbach, 1997 and 1993]. A platform design consists of a basic architecture, comprised of subsystems or modules and the interfaces between these modules. One of the main challenges when making a platform strategy is that innovative products are normally highly integrated. Analyzing the product architecture and decoupling it first is important to determine product modules with the right size and content.

Some of the companies (IBM during 90’s) have gone so far as plug-in-compatible modularity in cooperative work structure [Baldwin and Clark, 1997]. They have created product platform strategies that allow different parts of the organization to work independently on individual product modules. By concentrating on a single module the design complexity was properly managed and reduced. Design rules and interface management ensured that the modules did fit together.

Finally, complexity (C_p) can be measured through the degree of modularity a specific design possesses. In general, highly integrative products (or systems) represent a more

complex product, while modular designs (i.e. products) are less complex. That is, the degree of modularity determines the level of product complexity.

3.3. Process Complexity

One of the challenges in product development programs is to overcome the complexity involved in planning and executing large numbers of interconnected and interdependent design tasks. Success depends on management's ability to collect and process an overwhelming amount of continuously changing information for efficient decision making.

In enterprise integration information and communication technology are used to achieve dynamic alignment of resources through information and information systems. When concurrent engineering is implemented in order to reduce development time, design tasks can become complex taking even greater time to complete. The DSM [Eppinger, 1991; Steward, 1981] can be used to represent the constraints within a design process and explore optimal approaches for design process management. DSM is a tool, which allows development teams to visualize the relationship among the various design activities and reach consensus on what feedback loops are to be allowed.

Process complexity can be described as activity complexity. The higher the activity complexity is, the higher is the need for cognitive information processing and the higher is the probability of making design mistakes. The success in executing activities depends on available potential alternatives and an important element in that is creation and applying knowledge. Collaborative problem solving and activity flexibility depends on team assignment with an appropriate level of goal incongruence well as on the level of skill. Complexity of an activity is a measure of the cognitive problem-solving load that a certain activity will impose on the actors within the organization (figure 4) [Thomsen et al., 1998]. Activities that contribute to many different (possibly conflicting) requirements will require more cognitive energy than simple activities that relate only to one or two requirements. Activity complexity depends also on the difficulty of satisfying each individual requirement (i.e. requirement complexity). Requirement complexity increases as a function of the number of potential solution approaches in activities that contribute to the requirement. To determine the activity complexity, we add the requirement complexities of each of the requirements to which the activity contributes.

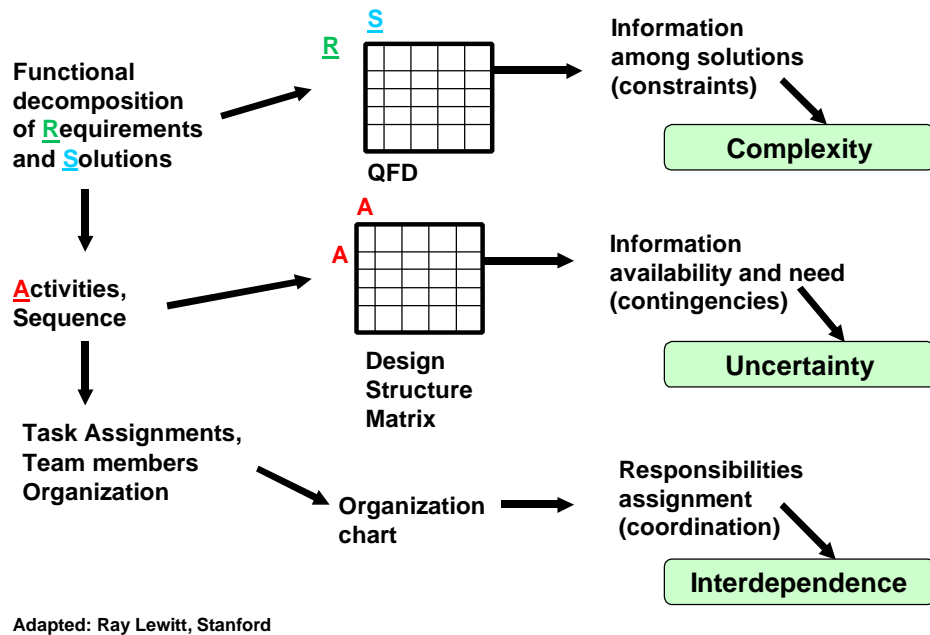


Figure 3. Managing semi-routine and fast-paced product development projects

Errors of judgment (technical oversight) and errors of skill (technical incompetence or lack of diligence) are both considered as technical errors. The probability that an activity will have a technical error is related to activity complexity as well as the match between skill requirements of the activity and the skill of the responsible design agent.

3.4. Organizational Complexity

Organizational complexity can be in the structure of the organization and in the behavior forms or procedures [Kelly and Allison, 1998]. It can also be in the networked environment and how organization is networked. Complexity can arise also from the individual behaving in networked environment and organization. It is also influenced by the deficit of individuals' or teams' capability when executing tasks they are responsible for. That shows us that enterprises should have a competence strategy showing how competence will be converted into human resource management and knowledge management.

Organizational complexity can be recognized when product architecture and people's architecture are mapped together. The bigger the mismatch between is, the higher the probability of committing design mistakes and consequently higher organizational complexity.

4. Framework for Complexity Reduction and Management

Many companies, from different sectors of industry, are changing rapidly towards a networked, virtual business. This kind of business strategy requires newly defined responsibilities, processes, models and tools. Moreover, it is only possible to implement through knowledge systematization, knowledge reuse, and better access to available and existing knowledge. In a collaborative, networked environment, a strategic management framework (figure 4) is required as a backbone for cooperation [Salminen et al., 2000].

Enterprises should decide on common information logistics and build common information models. After this step, it becomes easier for them to form cooperative processes and determine similarities and differences in their modeling practices and tools. Finally a common physical IT Infrastructure is necessary to make the cooperation possible. Users are influenced by a changing and dynamic business environment that cascades into the different hierarchies of organization. The strategic management framework, shown in Figure 4, will facilitate, automate and structure this cascading process.

The business environment plays a critical role in shaping and determining the processes that should be included in the strategic processes layer. The tools, models, and physical layers facilitate and support the execution of collaborative processes that are included in the strategic processes layer.

The strategic processes layer provides templates for a set of predefined processes applicable to a specific PD project. Processes can be added or deleted from this layer as necessary and as PD practices evolve within the collaboration with time.

The models layer contains consistent and up-to-date product, process, project, and organizational information. These models can range from simple Excel files to complex 3D solid models. The utilization of standard collaborative processes (defined in the processes layer) and a common tool set (as defined in the tools layer) allow these models to become a common language between development participants. There is no confusion to where a model is used, for what purpose, and with which tool.

The tools layer provides development participants with a consistent set of tools utilized during the executing of collaborative processes. These tools are accessible on demand to the whole development community. Tools might include CAD software (i.e. CATIA), PDM (i.e. metaphase), ERP (i.e. SAP), simulation, supply chain management (i.e. i2), and decision support tools to name a few. Again note that tools that should be included in this layer are dependent of a specific development environment. Finally, the tools layer would eliminate the need for duplication of tools within the development community.

The physical layer facilitates communication, information sharing, tools sharing, and ties up the distributed databases. Security issues are also addressed at this layer. This layer can simply be a computer network with a standard protocol for distributed computing such as CORBA.

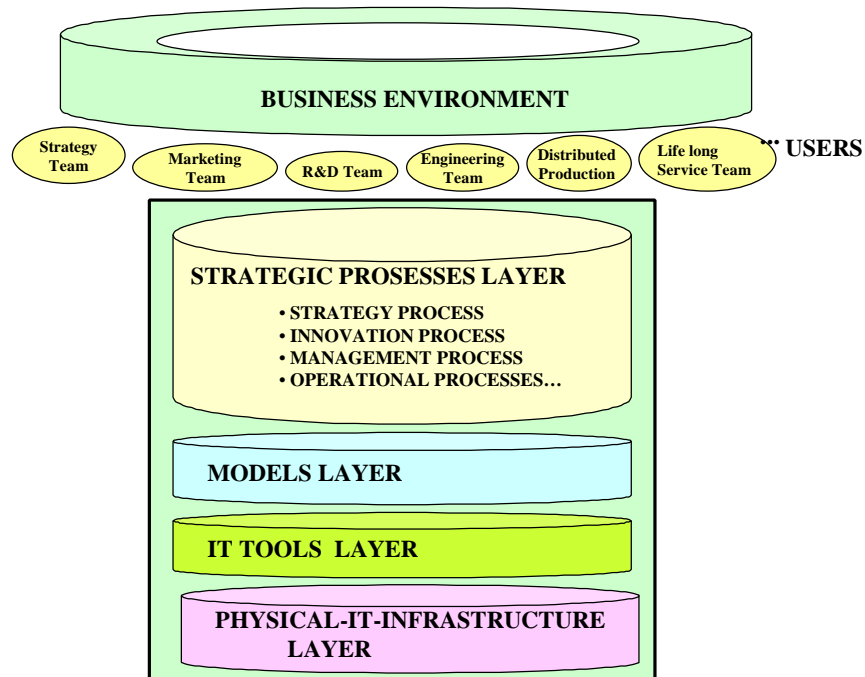


Figure 4. Conceptual Strategic Management Framework to manage complexity in distributed product development

Each layer, in the above framework, acts as a complexity multiplier. The challenge is how to measure the complexity of the product development process after passing through a specific layer. It is possible to explode or implode complexity during the execution of development processes as shown in figure 5. This is due to either using the wrong process, or model or tool during the execution of these processes. However, the proposed strategic management framework forces distributed users to utilize common, pre-determined, and streamlined processes. Furthermore, it provides a consistent set of models and tools to all development groups which results in less confusion among participants and reduction in PD complexity. Figure 6 shows the transformation of PD complexity as the PD process progresses through the framework.

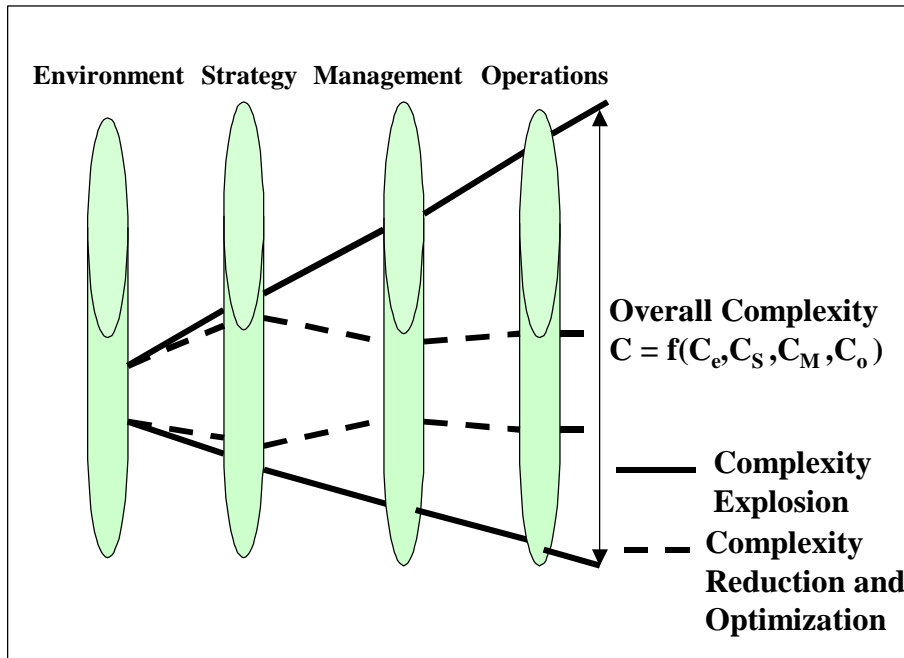


Figure 5. Complexity explosion and implosion/management

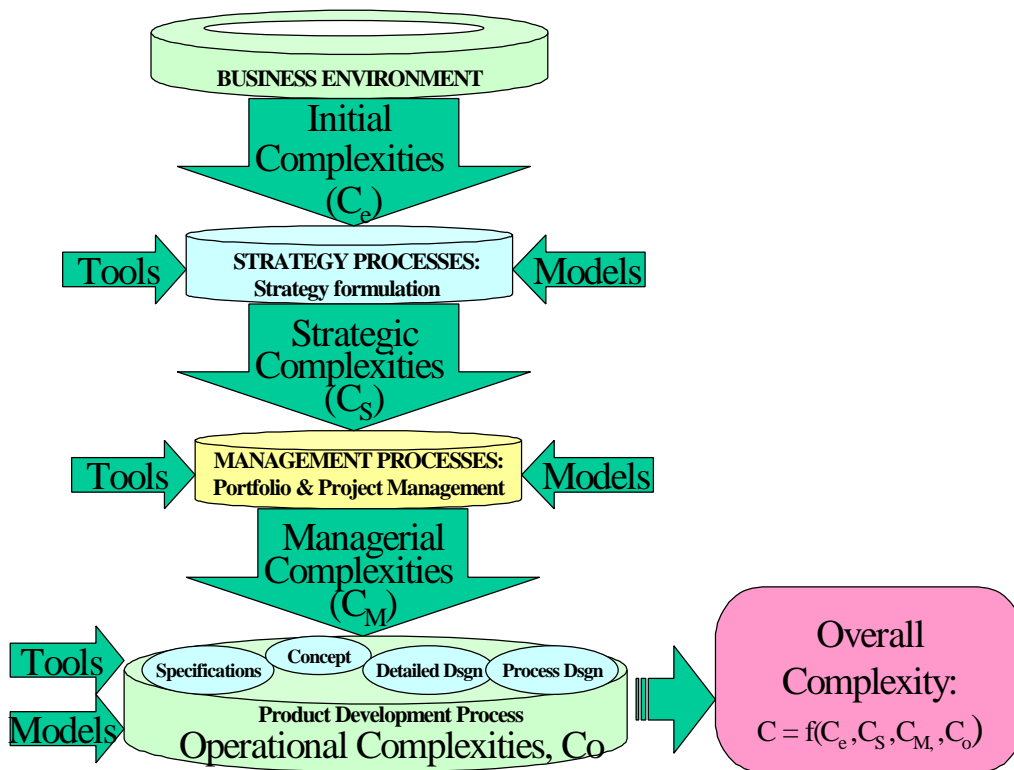


Figure 6. Complexity Multiplier Model (Complexity Flow-down model)

5. Summary

In this article we provided a survey of the literature on product development complexity and its management. We have also introduced a template for decomposing complexity into its various components in order to allow for better understanding, measurement, and management of PD complexity. These components can be aggregated to provide a single overall measure of PD complexity.

We have introduced a conceptual IT framework to manage and reduce PD complexity in a distributed environment. The framework helps virtual enterprises (i.e. distributed users) to formulize their PD processes and information logistics, and decide on common models and tools. This disciplined approach to distributed PD allows organizations to manage and reduce their PD complexity.

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